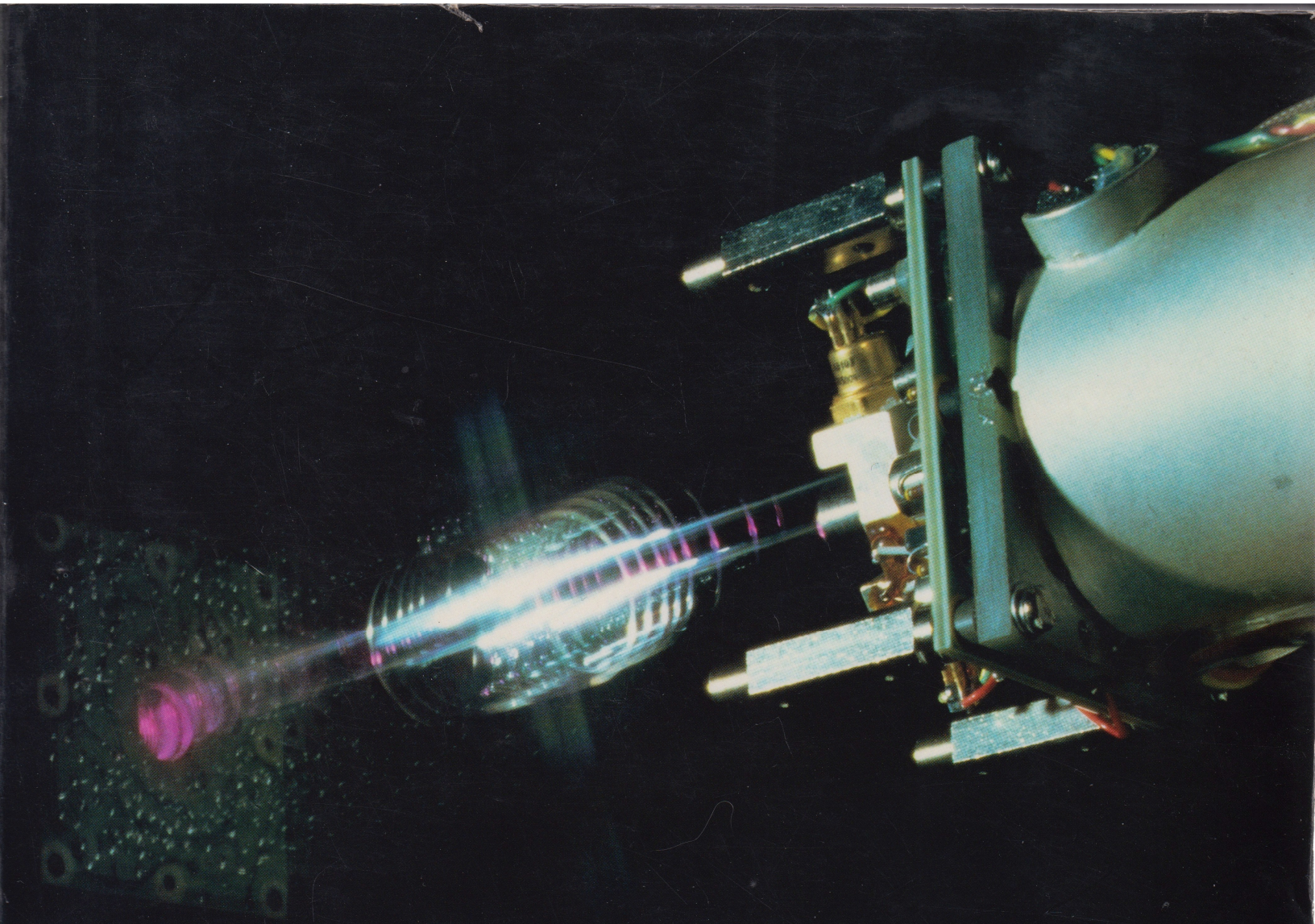
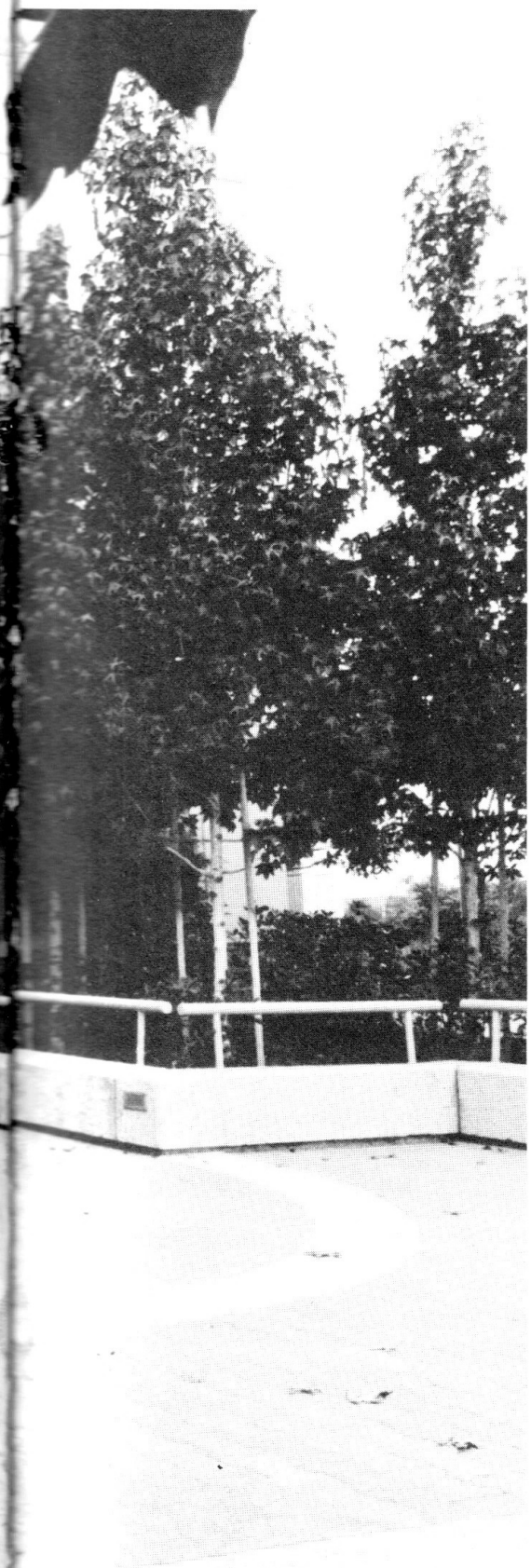
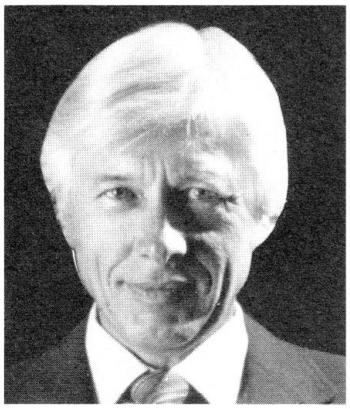


Ball Efratom Division

PRECISION TIME AND FREQUENCY HANDBOOK

EIGHTH EDITION





Virtually every sophisticated electronic system today requires an oscillator of some precision level, such as a clock and/or frequency generator. In the case of navigation, communications, and network control systems, the precision of the oscillator becomes even more important. As one advances even further to higher levels of sophistication such as spread-spectrum, crypto C3/I communication and one-way ranging and positioning systems, oscillator stability and performance become the system drivers, generally demanding the very best in quartz oscillator technology and most often, atomic oscillator precision.

This handbook provides information for better understanding of the time and frequency field and describes the four dominant precision oscillator technologies. Since EFRATOM specializes in two of these, the data herein primarily details the characteristics and applications of high precision quartz oscillators and miniature rubidium atomic oscillators. This data is designed to give the design engineer the tools to integrate such devices into his system.

Several sections of this handbook are devoted to the general oscillator subject, describing the types available, and how they work and mutually compare. The designer is also given tools on how to choose the proper oscillator for his requirements and explanations of the basic principles of one-way ranging, the spread-spectrum technology, and time/frequency transfer.

HUGO FRUEHAUF

PRESIDENT
BALL CORPORATION
EFRATOM DIVISION
Compiler of this book

PRECISION TIME & FREQUENCY HANDBOOK

3 Parker, Irvine, California 92718-1605, Telephone: (714) 770-5000, Fax (714) 770-2463, Telex: 685-635
Fichtenstrasse 25, 8011 Hofolding, (Munich) Germany, Telephone: 49-8104-9040, Fax: 49-8104-9918

Copyright 1991

SECTION TITLES

GENERAL INFORMATION	1.0	GENERAL INFORMATION ABOUT EFRATOM
	2.0	PRODUCT SUMMARY & SPECIFICATIONS
PERFORMANCE CHARACTERISTICS	3.0	PERFORMANCE SUMMARY
	4.0	ACCELERATION & VIBRATION
	5.0	Rb RADIATION HARDENING DATA
	6.0	Rb EMI SUMMARY
APPLICATION TOOLS	7.0	UNDERSTANDING THE SPECS
	8.0	CALIBRATION NOTES
	9.0	ERROR BUDGET NOTES
	10.0	APPLICATION TOOLS
TUTORIALS AND THEORY	11.0	ATOMIC OSC. THEORY OF OPERATION
	12.0	THE BASIC PRECISION OSCILLATORS
	13.0	TIME & FREQUENCY TRANSFER
	14.0	NAVIGATION AND THE OSCILLATOR
	15.0	SECURE-AJ COMMUNICATIONS AND THE OSCILLATOR

Index

GENERAL INFORMATION ABOUT EFRATOM 1.1
Ball Efratom Division Facility in Irvine, CA 1.3
Efratom Elektronik GmbH Facility in Munich, Germany 1.5
Ball Aerospace Systems Group- Organizational Chart 1.6
Ball Efratom Division- Organization Chart 1.7
Company History 1.9
Smithsonian Institution Display- Washington D.C. 1.14

PRODUCT SUMMARY & SPECIFICATIONS 2.1
Product Summary 2.3
Commercial Rubidium Oscillators 2.4
Military Rubidium Oscillators 2.5
Rubidium Frequency Standards 2.6
SC-Cut, OCXO Quartz Crystal Oscillators 2.7
Modular Time and Frequency Systems 2.8
Special Projects 2.9
Detailed Specification Sheets 2.11
The Time Base Sub-miniature Rubidium Oscillator - Model FRS 2.12
Model FRS Block Diagram 2.13
FRS-C Specification Sheet 2.14
FRS-N Specification Sheet 2.16
The Commercial Rubidium Oscillator - Model FRK 2.18
Model FRK Block Diagram 2.19
FRK Specification Sheet 2.20
The Military Tactical Rubidium Oscillator - Model M100 ..... 2.22
Model M100 Block Diagram 2.23
M100 Specification Sheet 2.24
The Sub-miniature Tactical Rubidium Oscillator - Model M3000 ..... 2.28
Model M3000 Block Diagram 2.29
M3000 Specification Sheet 2.30
The Super-miniature Mil. & Com'l. Quartz Crystal Oscillators -
Models EMXO/ECXO 2.32
Model EMXO/ECXO Block Diagram 2.33
EMXO Military Specification Sheet 2.34
ECXO Commercial Specification Sheet 2.36

Rubidium Frequency Standard - Model MRT 2.38
Model MRT Block Diagram 2.39
MRT Specification Sheet 2.40
MRT-HT Specification Sheet 2.42
Rubidium Portable Clock - Model PC-10 ..... 2.44
Model PC-10 Block Diagram 2.45
PC-10 Specification Sheet 2.46
VXIbus Rubidium Frequency Standard - Model VRFS-MC 2.48
Model VRFS-MC Block Diagram 2.49
VRFS-MC Specification Sheet 2.50
Modular Frequency & Time Systems 2.52
Model MFS Block Diagrams 2.53
Frequency Generators 2.56
Frequency Distributors 2.58
Frequency Calibrators 2.60
Frequency Synchronizers / RF Switches 2.63
Frequency / Phase Comparison 2.64
Power Supplies 2.65
Frequency Receiver and Clock Display 2.66
System Status 2.67

PERFORMANCE SUMMARY 3.1
The Four Basic Rb Oscillator Models Compared 3.2
M100 Power Consumption vs. Temperature (Details) 3.4
FRS, FRK, M100, M3000, EMXO Power Consumption vs. Temp. 3.5
M-100 Current vs. Supply Voltage 3.6
EMXO, ECXO Power Consumption Aging 3.7
FRK, M100, FRS, M3000, EMXO Warm-up Time vs. Temp. 3.8
M100 Warm-up Current vs. Time 3.9
M3000 Warm-up Current vs. Time 3.10
M3000 Warm-up Current vs. Input Voltage 3.11
EMXO Warm-up Time at -55°C, Measured Data 3.12
EMXO Warm-up Time vs. Oven Current at -55°C 3.13
FRS, FRK, M100, MK3000, EMXO Short-term Stability 3.14
M100, FRK Short-term Stability, Measured Data 3.15
FRS, FRK, M100, M3000, EMXO Phase Noise 3.16
M100-LN Phase Noise, Measured Data 3.17

FRK, M100, FRS, M3000, FRK-GPS, EMXO
Long-term Stability and Aging 3.18
FRS, FRK, M100, M3000, EMXO Magnetic Field Performance 3.19
EMXO Magnetic Field Performance, Measured Data, 10 Gauss 3.20
FRS, FRK, M100, M3000 Temperature Coefficient 3.21
M100-HC Temperature Coefficient, Measured Data 3.22
FRK, M100, MDRC Temperature Coefficient vs. Total Temp. Spread 3.23
EMXO Temperature Coefficient 3.24
FRS, FRK, M100, M3000, EMXO Pressure Sensitivity 3.25
FRK, M100 Typical Retrace Characteristics 3.26
EMXO Typical Retrace Characteristics 3.27
FRK, FRT Rubidium Oscillator Reliability Data 3.28
NAVSTAR #3 Rb After Being Off For 13 Years 3.30
EMXO Reliability Analysis 3.34
MIL-STD-704 Electrical Power Spec. Compatibility For M100 ..... 3.35
MIL-STD-704 Electrical Power Spec. Compatibility For M3000 ..... 3.36

ACCELERATION & VIBRATION 4.1
M100, M3000 Linear Acceleration 4.3
FRK, M100 Random Vibration vs. Allan Variance, Measured Data 4.4
M100-LN, S/N 637 Random Vibration vs. Allan Variance, Measured Data 4.5
Random Vibration vs. Phase Noise, Basic Rb Product 4.6
M100, M3000 Random Vibration vs. Time Error 4.7
M-100 Shock vs. Frequency Offset 4.8
EMXO G-Sensitivity 4.9

Rb RADIATION HARDENING DATA 5.1
General Information 5.3
Effect of 10^4 RADS (CO^{60}) On An Operating Rb Oscillator,
Commercial FRK, Measured Data 5.4
FRK Phase Noise vs. Radiation Dose, Measured Data 5.5
FRK NAVSTAR-GPS Rb Oscillator Dose Rate 5.6
FRK NAVSTAR-GPS Rb Oscillator Phase Error 5.7
M100 Gamma Flash Radiation Test, Measured Data 5.8

Effect of Neutrons, ~10^{13} n/cm^3 on an Operating M100, Measured. Data 5.11
Aberdeen Pulsed Reactor Fac. Neutron Tests, M100 Measured Data 5.12
Glass Radiation Data 5.13
Photocell Radiation Data 5.17
Summary of Radiation Effects on Physics Package Components 5.18
Conclusions 5.19

Rb EMI SUMMARY 6.1
M100 EMI Test Summary 6.3

UNDERSTANDING THE SPECS 7.1
Frequency and Time 7.2
Definition of Terms As Applied To Oscillators 7.3
Why "Allan Variance"? 7.5
What is "Allan Variance"? 7.6
Time Domain Stability 7.7
Power Law Dependence of $\sigma y(\tau)$ 7.8
Short-term Instability (Stability) 7.9
Freq. Noise & Allan Variance 7.10
Time Domain vs. Frequency Domain 7.11
Time and Frequency Domain and Time Error 7.12
Typical Behavior of Quartz Crystal Oscillators Due to Environmental Influences 7.13
Vibration-induced Allan Variance Degradation 7.14
Vibration-induced Sidebands 7.15
Phase Noise Under Vibration 7.16
Sine Vibration-induced Phase Noise 7.17
Random Vibration-induced Phase Noise 7.18

CALIBRATION NOTES 8.1
Efratom Rb Oscillator Calibration Ports 8.2
VCXO & C-field Adj. Explanations for Efratom Rb Oscillators 8.3
EMXO/ECXO Quartz Crystal Osc. Freq. Adjustment at EFC Pin 8.4
Omega/VLF Navigation Rb Calibration 8.5
Calculations For Δ Time & Frequency 8.6
Calculation Example For ΔT & Time-Between-Calibration (TBC) 8.7

ERROR BUDGET NOTES **9.1**
Environmental Changes vs. Performance Characteristics of a Rb Osc. 9.3
Time Error Calculation Notes 9.4
Time Error Due to "Aging" of Atomic Oscillators 9.5
Operational Considerations 9.7
Fighter Aircraft 4-hour Mission Profile,
Time Error Analysis M3000 ..... 9.9
Typical Mission Profile, Fighter Aircraft 9.17
Total Accum. Time Error, Combined Environments 9.18
Accum. Time Error, Acceleration 9.19
Accum. Time Error, Pressure 9.20
Accum. Time Error, Temperature 9.21
Accum. Time Error, Volts 9.22
Accum. Time Error, Magnetics 9.23
Accum. Time Error, Vibration 9.24
Accum. Time Error, Retrace 9.25
Accum. Time Error, Warm-up 9.26
Accum. Time Error, Aging 9.27
Accum. Time Error, Last Cal. 9.28
Fighter Aircraft 4-hour Mission Profile,
Time Error Analysis EMXO Quartz Crystal Oscillator 9.29
Typical Mission Profile, Fighter Aircraft 9.37
Total Accum. Time Error, Combined Environments 9.38
Accum. Time Error, Acceleration 9.39
Accum. Time Error, Pressure 9.40
Accum. Time Error, Temperature 9.41
Accum. Time Error, Volts 9.42
Accum. Time Error, Magnetics 9.43
Accum. Time Error, Vibration 9.44
Accum. Time Error, Retrace 9.45
Accum. Time Error, Warm-up 9.46
Accum. Time Error, Aging 9.47
Accum. Time Error, Last Cal. 9.48
Example Truck Mounted Rb Error Budget Analysis 9.49

APPLICATION TOOLS 10.1
Systems Design Consideration / Choosing the Osc. Best Suited For Job 10.2
Oscillator Selection Guidelines 10.4
Frequency Aging & Offset vs. Time Error 10.7
Allan Variance Comparison of Cesiums & Passive Maser 10.8
Measurement Time vs. Frequency Accuracy 10.10
Details of Precision Freq. Sources 10.11
Details of Precision Freq. Sources (Combined) 10.12
Useful Time & Frequency Relationships 10.13
Phase Noise Degradation Due to Vibration 10.14
Doppler Shifts 10.15
Quartz Oscillators-Types Stability vs. Power Consumption 10.16

ATOMIC OSCILLATOR THEORY OF OPERATION 11.1
The Generalized Atomic Oscillator 11.2
Figure 11-1. Magnetic Field Dependence of the Hyperfine Doublet 11.5
Figure 11-2. Block Diagram of a General Active Atomic Osc. 11.7
Figure 11-3. Block Diagram of a General Passive Atomic Frequency Std. 11.9
Figure 11-4. Concept for the Magnetic State Selection of the Upper & Lower Hyperfine States in an Inhomogeneous Magnetic Field 11.11
Figure 11-5. Concept for Optical Pumping Using a Three Level System 11.12
Figure 11-6. Concept of Microwave Resonance Detection Using the Optical Density of the Atomic Medium 11.14
Atomic Frequency Standard Types 11.16
Figure 11-7. Schematic Drawing of a Cesium Beam Tube 11.18
Figure 11-8. Electronic Schematic Showing the Frequency Lock of a Voltage Controlled Quartz Oscillator to an Atomic Resonance 11.19
Figure 11-9. Concept for the Detection of a Passive Resonance Using Sinusoidal Frequency Modulation 11.20
Figure 11-10. Schematic Drawing of the Atomic Spectrometer for a Passive Rb Frequency Standard 11.21
Figure 11-11. Schematic Drawing of an Active Hydrogen Maser 11.23
Figure 11-12. Schematic Showing the Phase Lock of a Voltage Controlled Qz Osc. (VCXO) to the Atomic Radiation Emitted by an Active Maser 11.25

General Theory of Operation of Efratom Rb Oscillators 11.27
Figure 11-13. Ground State Hyperfine Structure 11.28
Figure 11-14. Modulation Signal Concept 11.29
Figure 11-15. Simplified Block Diagram & Physics Package 11.30
Figure 11-16. Detailed Block Diagram 11.31
Figure 11-17. Electrical Analogue of Physics Package 11.36
Figure 11-18. Optical Pumping Process Illustrated 11.38
Figure 11-19. The Zeeman Effect 11.41
Table 11-1. ^{87}Rb Energy Level Separations 11.42
Figure 11-20. Rubidium Oscillator Block Diagram 11.46

THE BASIC PRECISION OSCILLATORS 12.1
High Performance Oscillators 12.2
Crystal Oscillator Categories 12.3
Main Categories of Quartz Crystal Oscillators 12.4
The Precision Quartz Oscillator 12.5
The Atomic Quartz Oscillators 12.6
Electromagnetic Spectrum 12.7
Basic Rubidium Oscillator Concept 12.8
Optical Pumping Process 12.9
Model FRS Rubidium Oscillator 12.10
Rubidium Physics Package Components 12.12
Physics Packages 12.13
The Rubidium Atomic Oscillator 12.14
Basic Cesium Beam Oscillator Concept 12.15
Basic Operation of Cesium Beam Oscillator 12.16
The Cesium Atomic Oscillator 12.17
The Hydrogen Maser Atomic Oscillator 12.18
Basic Active H-Maser Concept 12.19
Active vs. Passive H-Maser 12.22
General Comparison of Precision Oscillators 12.24
General Comparison of High-Performance Osc. Frequency Stability 12.26
The Future of Precision Oscillators 12.28

TIME AND FREQUENCY TRANSFER 13.1
What Is Time? 13.2
Past, Present, and Future of Atomic Timekeeping 13.3
Definition of Terms for Time & Time Transfer 13.9
Relative vs. Systems Time Synchronization 13.11
Time/Frequency Transfer Via Portable Clock Technologies 13.12
Time Transfer Via NIST Goes Satellites 13.13
Time & Frequency Transfer Via NAVSTAR-GPS Satellites 13.15
Common-View Time & Frequency Transfer Concepts Via GPS 13.16
UTC (Universal Coordinated Time) Transferred Via GPS 13.17
NAVSTAR-GPS Time Definition/Quality 13.18
Synchronization Capabilities From Various Systems 13.19
Efratom MDRC Time/Frequency Modular Systems 13.20
Why Discipline a Rb Oscillator? 13.21
Block Diagram of Efratom MDRC, GPS Disciplined Rb T/F System 13.22
Typical MDRC Performance With Full GPS Coverage 13.23
Typical MDRC Performance With Degraded GPS Coverage 13.25
DRC Performance With Degraded GPS Coverage 13.26
Positioning Data Is Needed To Obtain Accurate UTC 13.27
GPS RCVR & Oscillator Attributes 13.28
NAVSTAR-GPS Satellite Clock Stability Performance 13.29

NAVIGATION AND THE OSCILLATOR 14.1
Historical Perspective 14.2
Methods of Navigation 14.3
The Historical Development of Accurate Clocks 14.4
Common 2-Way Ranging System 14.5
More Complex 2-Way Ranging System 14.6
Common 1-Way Ranging System 14.7
Electronic 1-Way Ranging System 14.8
Spaceborne 1-Way Ranging System 14.9
The NAVSTAR GPS 14.12
NAVSTAR GPS Accuracy 14.14
Determining The GPS Navigation Accuracy 14.15
GPS Corrections to the Navigation Accuracy 14.16

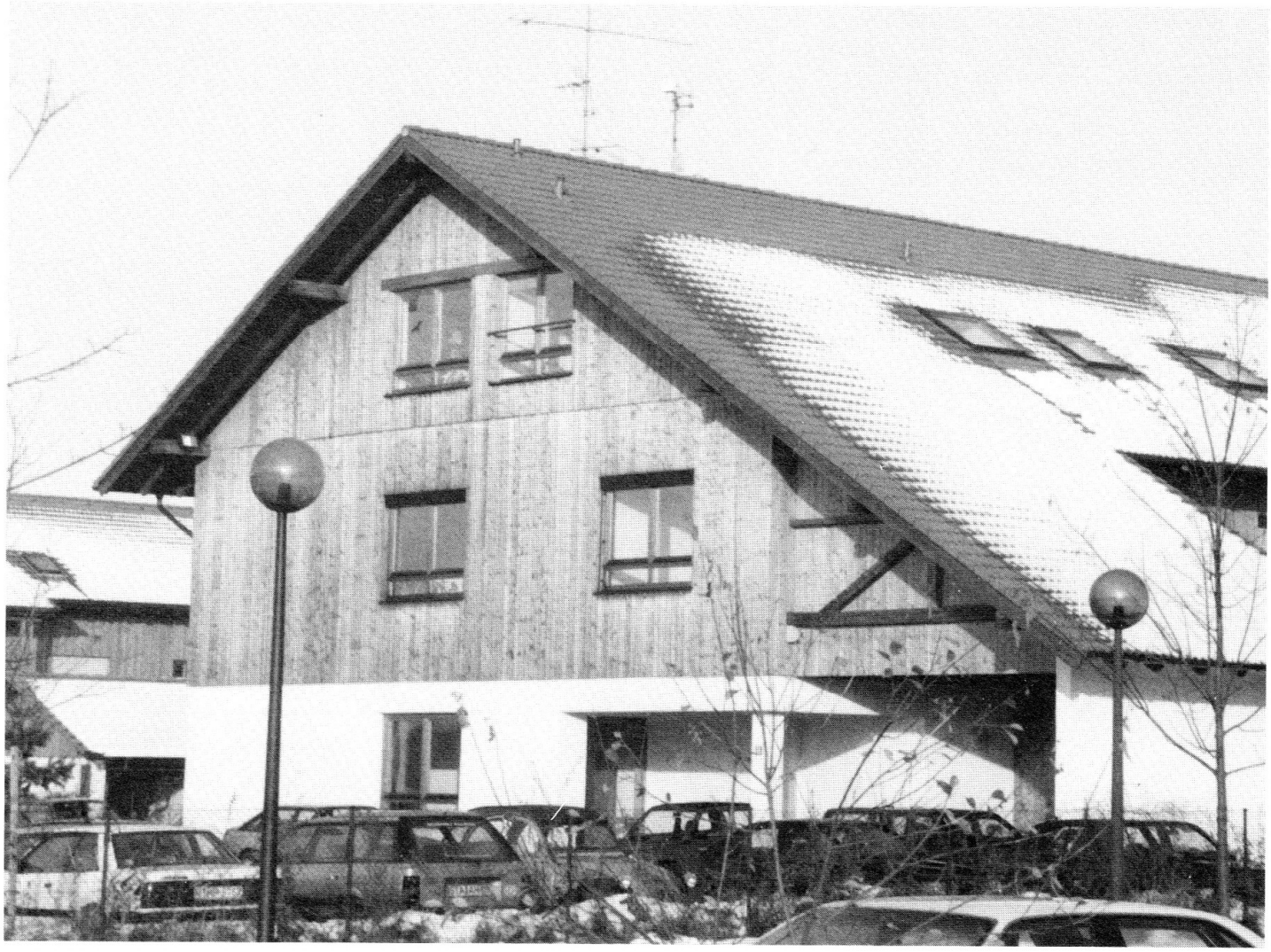
GPS Corrections To The Navigation Solution 14.17
The Transit Navigation Satellite 14.18
LORAN-C 14.20
OMEGA 14.22
OMEGA Navigation 14.24
OMEGA's Lane Ambiguities 14.25
OMEGA Uses Staggered TDMA Transmissions For Transmitter Identification 14.26
JTIDS RELNAV (Joint Tactical Information & Data System) 14.27
PLRS (Position Location & Ranging System) 14.29
Why Use Atomic Oscillators For Navigation? 14.31

SECURE-AJ COMMUNICATIONS & THE OSCILLATOR 15.1
Spread Spectrum 15.2
Basic Spread Spectrum System 15.3
Spread Spectrum Process 15.4
Pseudo-Noise (PN) Direct Sequence Spread Spectrum 15.5
PN-Receiver 15.6
FH-Receiver 15.7
TH-Receiver 15.8
Spread Spectrum Techniques Compared 15.9
Acquisition Time vs. The Oscillator 15.10
Oscillator Impact On NAV Or Spread Spectrum Terminal Performance 15.11
Oscillator Specs/Environment/SP.SP. Impact 15.12
Example System (NAVSTAR-GPS) 15.13
Modulation-NAVSTAR-PRN 15.14
FH-Have-Quick System Example 15.15
TH-JTIDS-TDMA System 15.16
Clock For Very Fast Frequency Hopping Radio 15.18
Bistatic Radar 15.19
Identification-Friend-Or-Foe (IFF) 15.20
What Is Coherent Transmission? 15.22
Why Use Atomic Osc. In Spread Spectrum & Secure Comm.? 15.23

GENERAL INFORMATION ABOUT EFRATOM

Ball Corporation, Efratom Division facility in Irvine, California

The company occupies approximately 60,000 square feet in the facility pictured, including space in an adjacent building. The facility is part of a modern, newly constructed business park, about 10 miles south of the John Wayne Orange County Airport in Southern California's Los Angeles area.



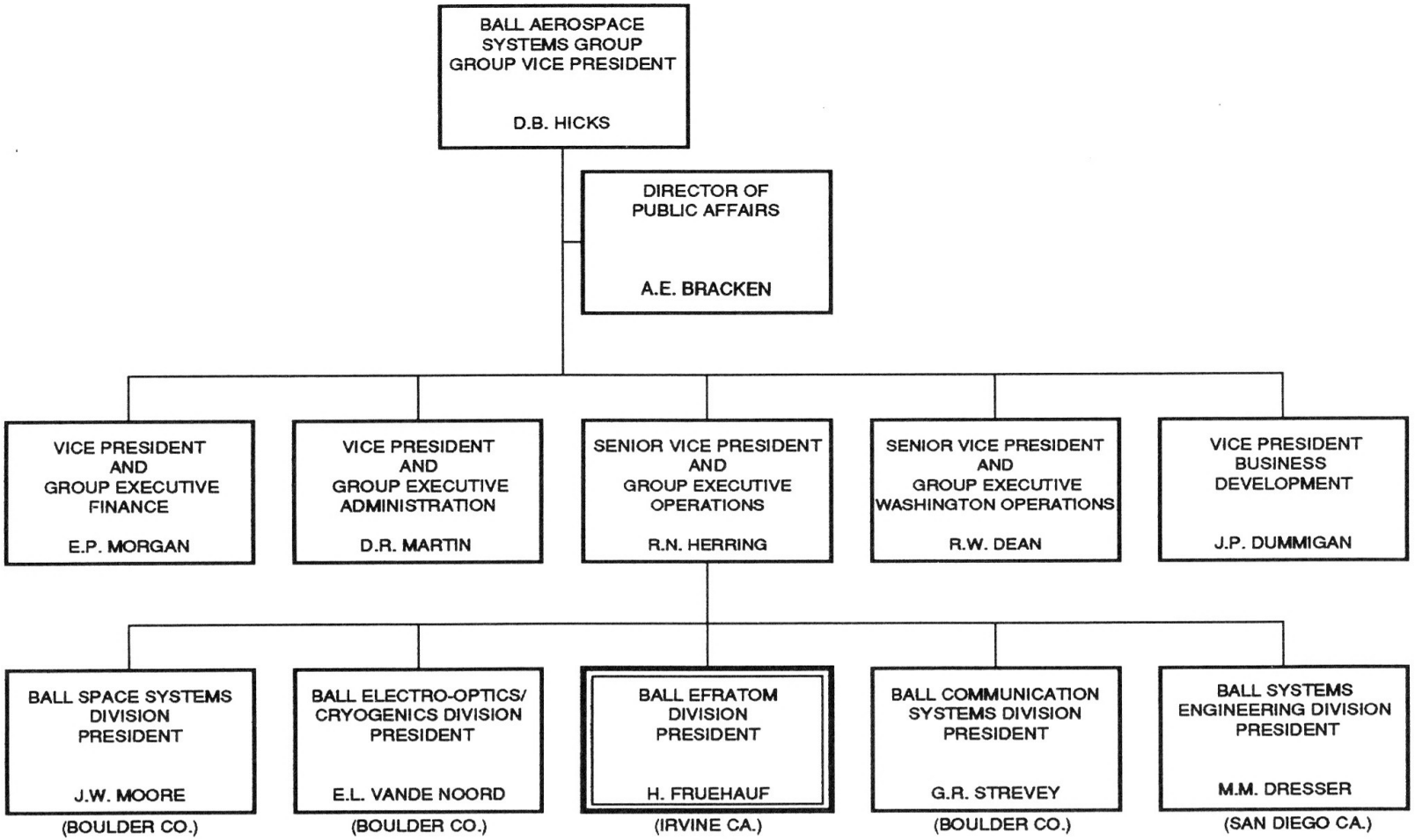
Ball Corporation, Efratom Elektronik GmbH, Hofolding (Munich) Germany

The company also occupies approximately 12,000 square feet in this facility, about 10 miles south of Munich.

The California and Munich facilities have independent R&D and rubidium/ physics capability and basically produce the entire product line in each location. California and Munich operations interact in design and production as economics and markets demand.

BALL AEROSPACE SYSTEMS GROUP ORGANIZATIONAL CHART

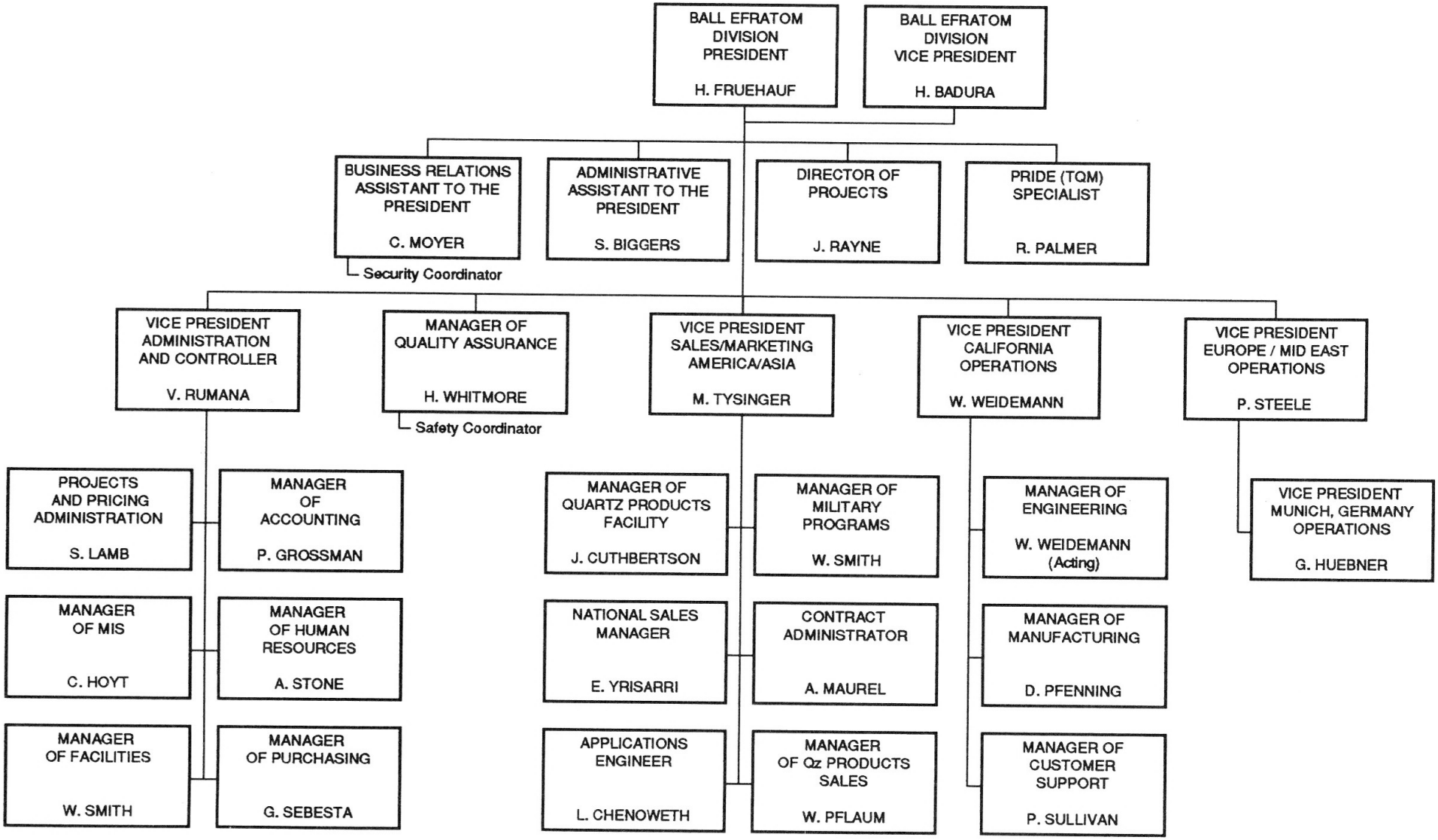
Ball Efratom Division



JANUARY 1, 1991

BALL EFRATOM DIVISION ORGANIZATIONAL CHART

Ball Efratom Division



1.7

JANUARY 1, 1991

Ball Efratom Division History and Facilities

Efratom is a division of the Ball Aerospace Systems Group (BASG) headquartered in an area near Boulder, Colorado. BASG is part of the Ball Corporation, a Muncie, Indiana company. The group is dedicated to high technology which includes satellites, space instruments, navigation sensors and trackers, control/pointing systems, communications related electronics, antennas, cryogenic systems, simulators, analytical services, precision time and frequency generators and a host of other electronic and electro-mechanical systems. Efratom, headquartered in Irvine, California, is one of five divisions contributing to this technical base, focusing its total effort on the time and frequency technology.

In 1982 Efratom became part of the Ball Corporation. Prior to that period, Efratom was a wholly owned company founded in 1971 in Munich, Germany by Ernst Jechart and Gerhard Huebner. They are the pioneers who developed the technological breakthroughs that resulted in the world's first minature rubidium atomic oscillator.

The R & D effort resulted in two patents which form the basis of the minature rubidium frequency standard technology. The U.S.A. patents are: #3,903,481-Alkali Vapor Isotope Ratios and #3,798,565-Compact Gas Cell Design. These patents are also granted in many other countries. The optical filter, which was traditionally located between the rubidium lamp and the rubidium resonance cell, was abandoned, using instead the patented isotope mixture filter design. The commonly used large TE_{011} cavity that encloses the resonance cell was replaced with a much smaller design that uses the TE_{111} mode.

These and numerous other innovations resulted in a totally new integrated design for Rb atomic oscillators more suitable to quantity fabrication and quality control. This work transformed what had been known as a cumbersome and delicate laboratory instrument into a small and rugged field component. National Institute for Science and Technology (NIST) measurements have shown that the minaturized standards meet or exceed the accuracy and stability of conventional laboratory-type designs.

In 1972 the first units were sold and proved to be an immediate success. Government agencies, industrial concerns, and television and radio networks all over the world procured the new units. In the spring of 1973, Jechart moved to the United States and the company became known as Efratom California, Inc., headquartered in Irvine, California. Huebner remained in Germany and to this date, directs Efratom Elektronik GmbH in Munich. The product became so successful worldwide that more than 35,000 Rb oscillator products have been sold to date, making Efratom the world's leading manufacturer of atomic oscillators. Markets served by these products are:

Communications systems such as telephone networks Stratum I & II timing, TDMA cellular ground stations, Mobile Subscriber Equipment (MSE), satellite ground stations of all types (commercial and military), simulcast communication systems, military communications systems such as Have Quick, Regency, Milstar, and a host of Tri-Tac, strategic and NATO systems using crypto spread spectrum/troppo-scatter transmission media in the ELF, LF, HF, UHF, SHF and EHF frequency bands.

Navigation systems such as Omega/VLF and Loran-C systems, satellite and user equipment of the Navstar Global Positioning Satellite systems network, PLRS, JTIDS, J-STARS and a host of others.

Special Applications such as instruments, test stations, calibration networks, laboratories, radars, signal generators and analyzers.

The goal of Efratom and all its employees is to meet the requirements of their customers and maintain the company's position of leadership in the design and production of time and frequency systems based on quartz crystal and rubidium atomic oscillator technologies.

Efratom occupies facilities totalling about 60,000 sq. ft. in Irvine, California and 12,000 sq. ft. near Munich, Germany, each capable of independent design, development and fabrication of precision oscillators and time/frequency systems. Efratom produces both commercial and full mil spec approved hardware. The name EFRATOM was coined from Electronic Frequency Rubidium ATOMic.

Progression of Development

The development progression sequence started with the commercial model FRK rubidium oscillator which formed the basis of the product line. Full-military versions followed, comprising our models M100, M1000, and the most recent M3000 Rb oscillators. A sub-miniature commercial rubidium oscillator was developed in the mid-80's, model FRS.

A line of instruments based on the oscillator technology was then developed. These instruments are oriented toward laboratory standards, precision oscillator performance measurement devices and time/frequency transfer products.

Next, a modular time and frequency system was developed which provides the customer with "semi-custom" 19 inch rack technology. These racks are assembled from standard plug-in modules that provide the customer with frequency generators, calibration and switch-over modules (for redundancy), various output buffers, a time code generator, a VLF/LF frequency/time receiver, a phase comparator and a Rb/GPS receiver discipline module. All of these, of course, are supported by power supply and battery modules, as well as circuitry for monitoring, Bite and alarm functions.

The Efratom technology base has also been broadened by the development of an SC-cut quartz resonator and oscillator, models EMXO and ECXO. The design of these units is geared for commercial and military applications requiring low-power, very-high precision quartz OCXO performance in a small package with fast warmup.

Pride in Excellence

Efratom has embarked on the monumental effort to become a World Class Quality company implementing the best of WCM, TQM, JIT, SPC and other world class quality systems. Efratom has dedicated itself to quality as a way of life. This effort, which started in late 1989, is called "Pride" (Pride In Excellence) and is permeating all departments and all activities. Although we have a long way to go in becoming a world class quality company, we are determined to succeed.

Separate commercial and military production lines are maintained to assure proper adherence to applicable quality standards and product reliability. Efratom is qualified to MIL-I-45208A and can manufacture to MIL-Q-9858. The required quality control procedures are fully integrated into the Efratom production process.

Product Support

Customer requirements often demand detailed technical support. As a result, Efratom offers engineering assistance in product design, development and application. Experience includes special capability in:

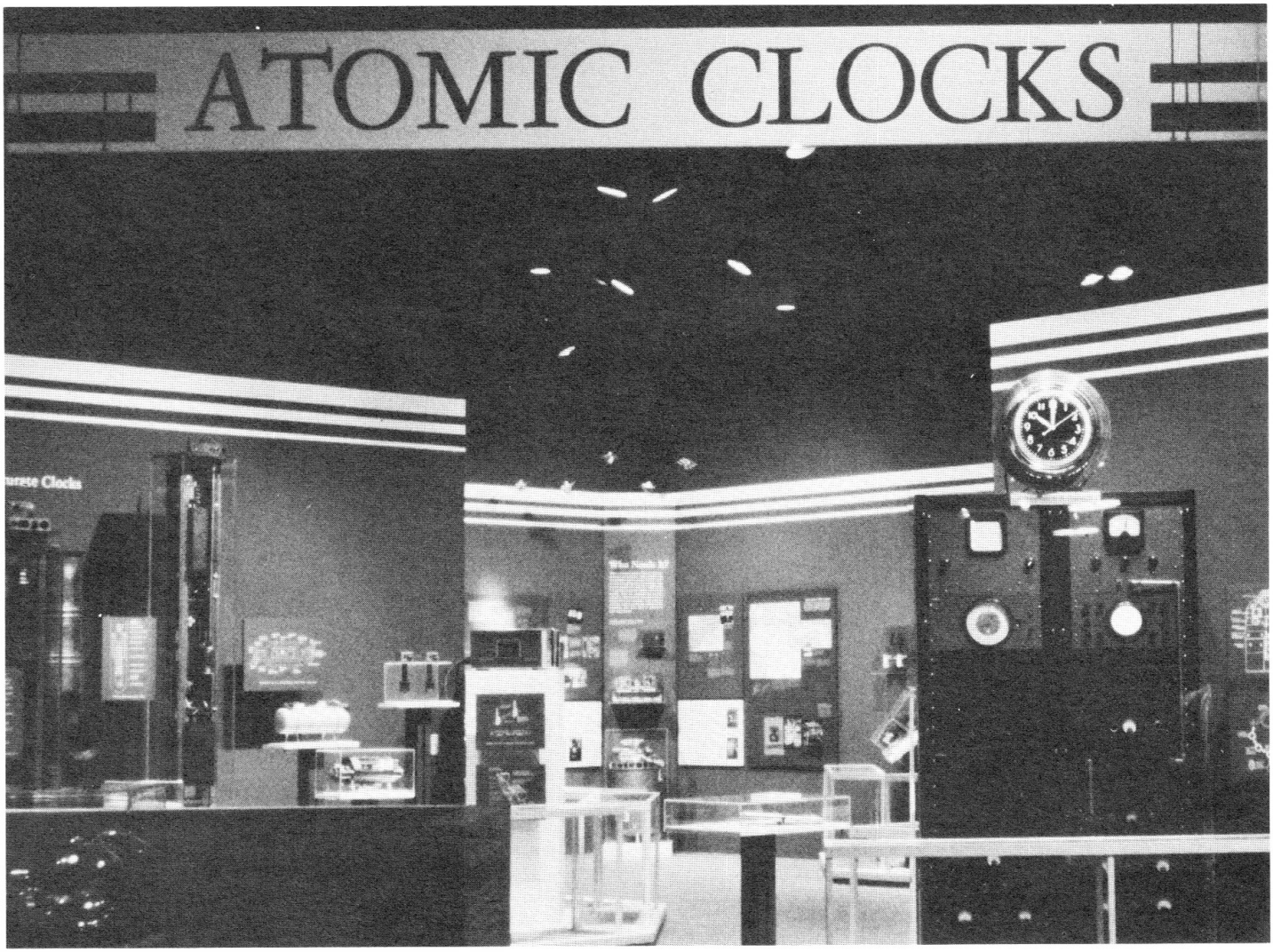
- Systems design and analysis for oscillator applications
- Frequency chain, synthesis, and distribution
- Test equipment to measure low phase noise and time domain stability
- LF/VLF receiver design and technology
- Power supplies, back-up battery systems, and redundancy concepts
- Time display, digital clocks, and time code generators.
- Time & frequency error budget analysis and systems integration.

Research and Development

To further the advancement of precision time and frequency technologies, Efratom is actively engaged in research and development. Goals are:

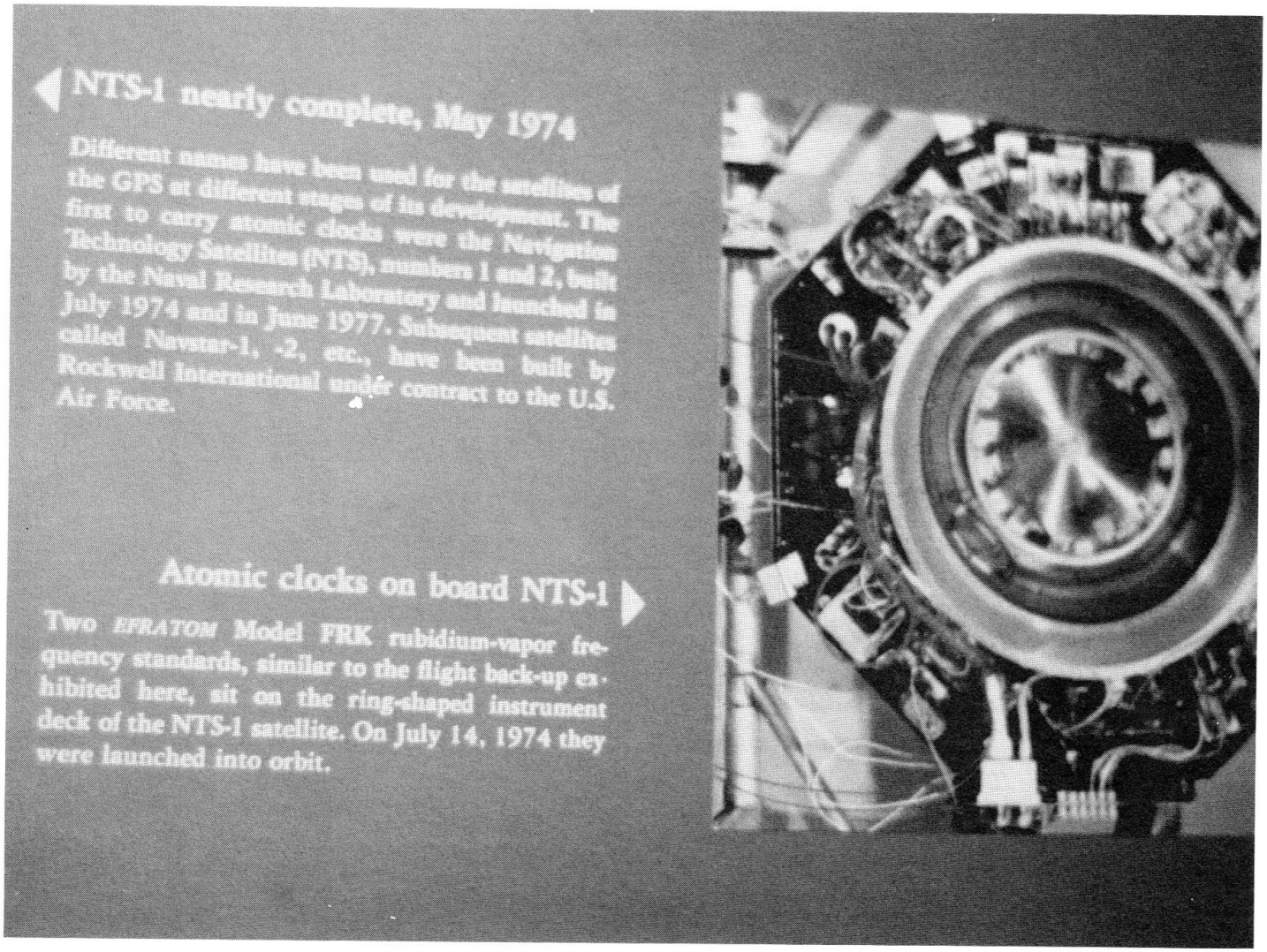
- Improved performance
- Decreased size and weight
- Lower costs
- Higher reliability

This research is combined with innovative design improvements in electronic circuits that allow the crystal oscillator, the rubidium oscillator, test equipment products and systems to maintain their position of leadership in this technology.

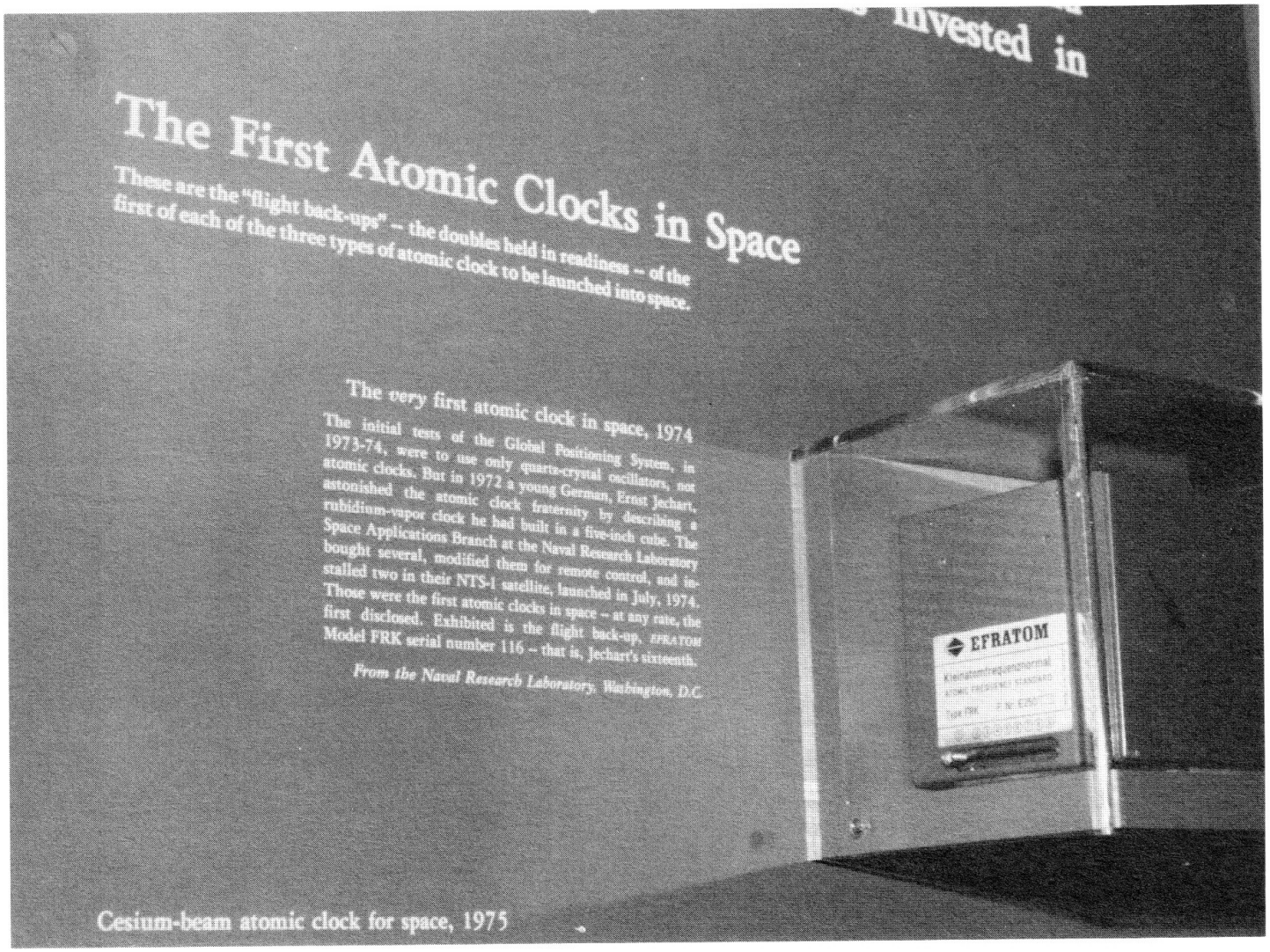


Smithsonian Institution Display, Washington, D.C.

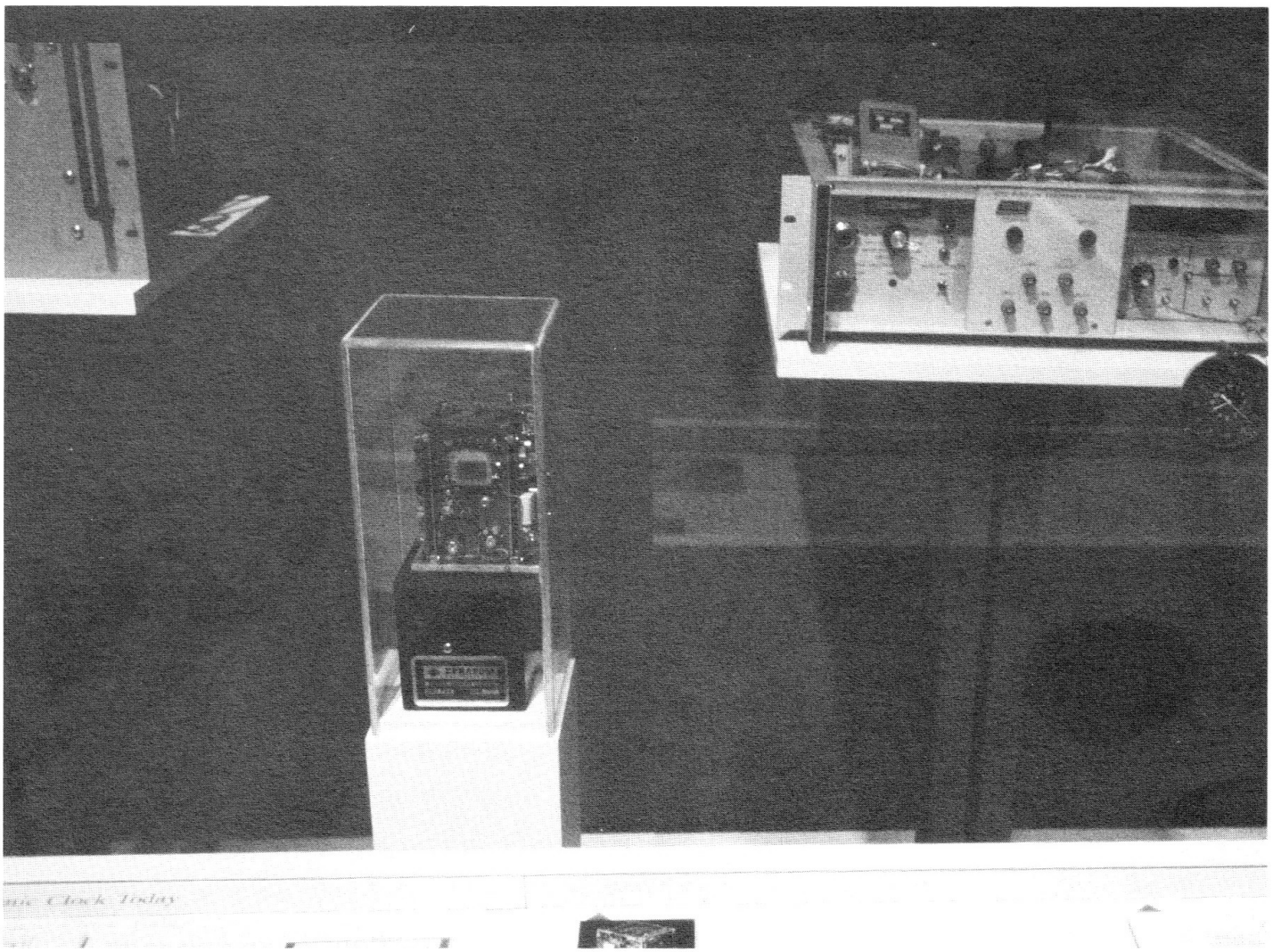
The Ball Efratom rubidium product is considered so unique that a major display was set up in the Smithsonian Institution, Washington, D.C. between 1982 and 1988. The Model FRK was part of an atomic oscillator display in the American History Museum portion of the institution. It displayed the FRK as the world's first miniature atomic oscillator and the first atomic oscillator in orbital space.



Smithsonian Institution Display, Washington, D.C.



Smithsonian Institution Display, Washington, D.C.



Smithsonian Institution Display, Washington, D.C.

PRODUCT SUMMARY & SPECIFICATIONS

Product Summary

Rubidium Atomic Oscillators

FRS	Sub-miniature com'l Rubidium Time Base Oscillators
FRK	Miniature com'l High Performance Rubidium Oscillators
M100	Miniature mil High Performance Rubidium Oscillators
M3000	Sub-miniature mil Tactical Rubidium Oscillators

Quartz Crystal Oscillators

EMXO	Super-miniature mil SC-cut Quartz Crystal Oscillators
ECXO	Super-miniature com'l SC-cut Quartz Crystal Oscillators

Rubidium Frequency Standards

MRT	(½) 19" rack Rubidium Frequency Standards
PC-10	Rubidium Portable Clock
VRFS-MC	VXIbus Rubidium Frequency Standard

Modular Time & Frequency Systems

MRK, MXO	Quartz Crystal and Rubidium Frequency Generators
MBFs	Frequency Distribution/Buffers
MDCs	Rubidium Calibration, Phase Locking/Redundant Switching of two Frequency Generators, and GPS Disciplining of Rubidium Oscillators
MPC	Phase Comparator
MPS, MBU	Power Supply and Backup Battery Module
MVLF	VLF/LF Frequency and Time Receiver with Display
MRTC	Clock Display/IRIG Time Code Generator
MSS	Bite and System Status Functions

Special Projects

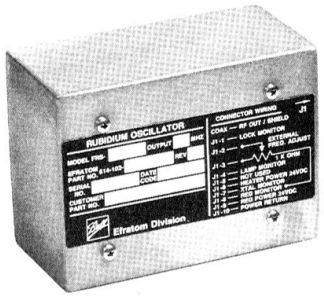
RFS	GPS Satellite Rubidium Oscillator

PRODUCT LINE SUMMARY

Ball Efratom Division

Commercial Rubidium Oscillators

FRS-C,N



The models FRS-C and N are the most compact atomic oscillators available and have been designed to maximize performance in the smallest package possible at a low cost.

Frequency Aging/month	:	5E-11
Phase Noise	:	1 Hz from carrier -70 dBc
	:	100 Hz -100 dBc
	:	1kHz -130 dBc
Operating Temperature	:	C -5°C to +65°C (Base Plate)
	:	N -55°C to +65°C (Base Plate)
Warm-Up	:	6 minutes to reach 1E-9 at +25°C Ambient
RF Outputs available	:	10, 5 MHz Sine
	:	10, 2.048 MHz TTL
Size	:	2 x 3 x 4 inches (100 x 99 x 112 mm)

FRK-L,H,LN

The models FRK-L,H,LN have the best stability and phase noise characteristics in the Ball Efratom range of atomic oscillators.

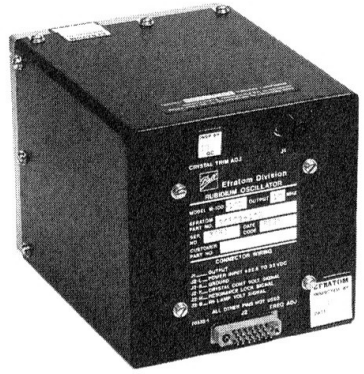
Frequency Aging/month	:	L 4E-11,	H 1E-11	
Phase Noise L and H	:	Without LN	With LN	With LN
	:	10 MHz	10 MHz	5 MHz
10 Hz from carrier	:	--	120	125
100 Hz	:	120	147	155
1 kHz	:	145	147	155
Operating Temperature	:	-25°C to +65°C (Base Plate)		
Option	:	-55°C to +65°C (Base Plate)		
Warm-Up	:	10 minutes to reach 2E-10 at +25°C Ambient		
RF Outputs available	:	10, 5 MHz		
Size	:	3.9 x 3.9 x 4.4 inches (100 x 99 x 112 mm)		

PRODUCT LINE SUMMARY

Ball Efratom Division

Military Rubidium Oscillators

M100



The M100 is fully radiation hardened and is considered a standard for Military Tactical Rubidium Oscillator Application. The unit has been qualified by the Army, Navy and USAF and presently serves a variety of military time/frequency systems.

Frequency aging/month	:	Std. 6E-11, option 1E-11	
Phase Noise	:	Std. (10 MHz)	100 Hz from carrier >130 dB
	:		1k Hz >140 dB
Low Noise Option		LN (5 MHz)	300 Hz >155 dB
Operating Temperature	:	Std. -55°C to +68°C (Base Plate)	
Option	:	HC -55°C to +75°C (Base Plate)	
Warm Up at +25°C	:	10 minutes to reach 2E-10 at +25°C Ambient	
RF Outputs Available	:	10, 5 MHz Sine	
Size		3.94 X 3.9 X 4.81 inches (100 X 99 X 122 mm)	

M3000

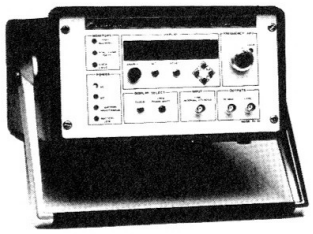
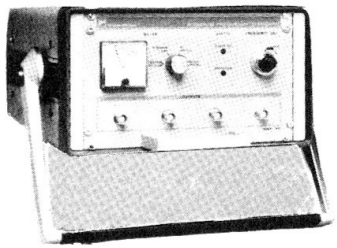
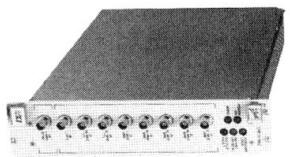
The M3000 meets the most severe military requirements. It is fully radiation hardened and will operate over a very wide temperature range. It provides high stability even under severe vibration with fast warm-up.

Frequency aging/month	:	6E-11	
Phase Noise	:	M3050 (5 MHz)	M3100 (10 MHz)
1 Hz from carrier	:	-90 dBc	-85 dBc
100	:	-143 dBc	-140 dBc
300	:	-150 dBc	-150 dBc
1 kHz	:	-155 dBc	-155 dBc
Operating Temperature	:	-55°C to +74°C (Base Plate)	
Warm Up at -55°C	:	5 minutes 2E-9 at -55°C	
		10 minutes 5E-10 at -55°C	
Size		3.25 X 3.25 X 4.5 inches (82.5 X 82.5 X 114 mm)	

PRODUCT LINE SUMMARY

Ball Efratom Division

Rubidium Frequency Standards

PC-10 	The model PC10 Atomic Portable Clock/Frequency Standard is a self-contained instrument which is designed for both laboratory and portable field operation. The PC-10 provides precise time of day information, a precision 1-PPS CMOS/TTL compatible signal and 10,5,1 and 0.1 MHz sinusoidal outputs. The basic reference frequency and all timing functions are derived from a highly stable internal Rubidium Oscillator. Sync capability and time difference readout between the internal 1-PPS to an external 1-PPS signal are provided. The unit can be operated from either an ac or dc power source, including field operation of up to 6 hours on internal batteries.
MRT 	The Model MRT Rubidium Frequency Standard is a self-contained instrument consisting of the Ball Efratom Model FRK-L/H Rubidium Oscillator, dividers, buffer amplifiers and a regulated power supply including stand-by batteries. The MRT is available for rack mount installation, occupying half the width of a standard 19 inch rack, with 5.05 inch panel height or with a portable instrument case for laboratory or field use. Buffered outputs of 10,5,1 and 0.1 MHz sine waves are provided at the front and rear panel connectors, as well as 1-PPS or special frequencies.
VRFS-MC 	The Model VRFS-MC is an ultra-stable miniature atomic oscillator suitable for use as a VXIbus system clock. The VRFS-MC is housed in a module that is designed to be installed in a C-size mainframe configured in accordance with This module is a message-based device that offers timing accuracy of ±1 ppb over its specified operating temperature at the VXIbus system clock frequency of 10 MHz and provides up to eight outputs (1 PPS, 1 MHz sine, 10 MHz sine, and 10 MHz TTL) and allows one 1 PPS input from an external source.

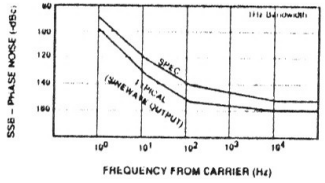
PRODUCT LINE SUMMARY

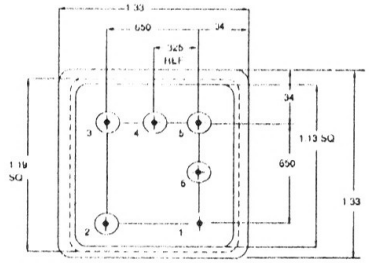
Ball Efratom Division

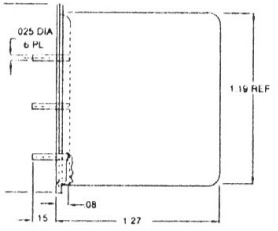
SC-Cut, OCXO Quartz Crystal Oscillators

EMXO and ECXO

Phase Noise







The model EMXO and ECXO are ultra-stable sub-miniature OCXO crystal oscillators designed for a wide variety of applications including radio navigation using Omega/VLF, Loran-C and satellite transmissions (GPS, TRANSIT, GOES); geophysical survey positioning systems; communication systems; time interval generation and transfer.

The outputs provide excellent short and long term stability over a wide range of environmental conditions.

These rugged, compact crystal oscillators are especially advantageous when utilized in mobile/transportable and portable applications where fast warm-up, low power consumption and small size are the key requirements.

SPECIFICATIONS	EMXO (Military)	ECXO (Commercial)
Very Low Power: <0.4W (TTL) at 25°C	√	√
Fast Warm-up: 4 minutes to 1E-8 of Final Frequency	at -55°C	at 0°C
Wide Operating Temperature Range	-55°C to +95°C	0°C to 50°C
Temperature Coefficient	±1E-8	±1E-9
Short-term Stability, 0.1 to 10 Sec: 5E-12	√	√
Frequency Aging: 5E-10/Day, 5E-8/Year	√	√
Outputs Available: 10, 10.23 MHz, Sine, TTL*	√	√
Size: 1.3 x 1.3 x 1.3 inches (32 x 34 x 34 mm)	√	√
Weight: 40 grams	√	√
Accel. Sensitivity: 1E-9 Per G	√	
Airborne Transport MTBF: Up to 330,000 Hrs.	√	
Full MIL Spec, Rad. Hard & Qual. Tested	√	

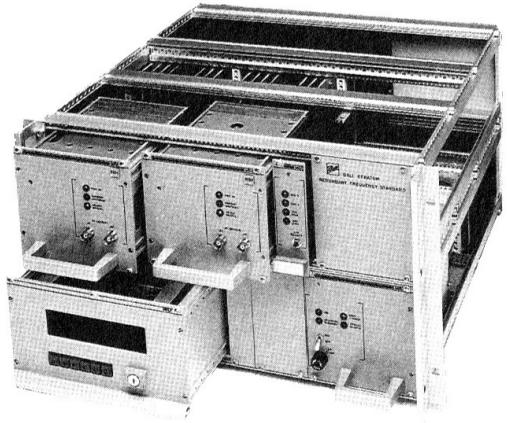
* Special frequencies on request

PRODUCT LINE SUMMARY

Ball Efratom Division

Modular Time & Frequency Systems

Front View (Example)

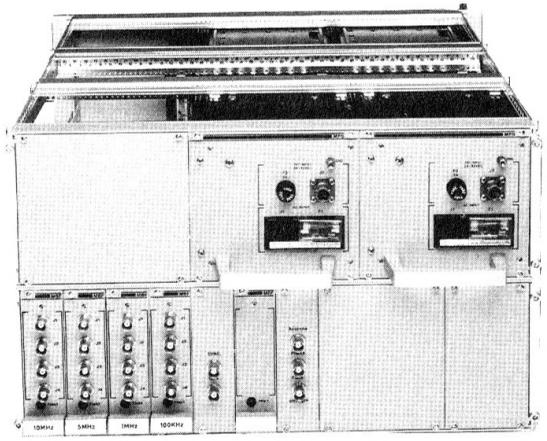


Semi-custom, 19 inch Rack Modular Time and Frequency Sytems assembled to meet the needs of the customer.

In this example, the two MRK Rubidium Oscillator modules are phase locked and automatically switched as necessary through the MDC-RR module to provide redundancy.

The MVLF (VLF/LF) Receiver or a GPS Receiver/Discipline Module (MDRC) automatically corrects the aging of the primary MRK Rb Oscillator to provide traceability to National Standards for both oscillators.

Rear View

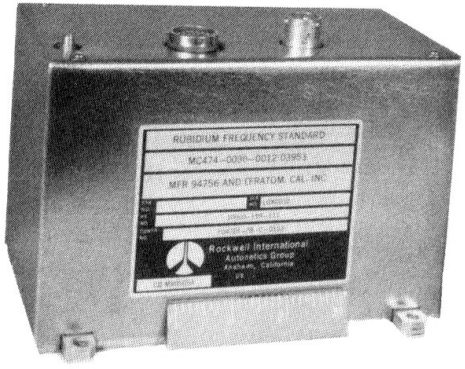


The two MPS power supplies provide redundancy and can be powered from either ac or dc. The MBU batteries provide internal power to guard against the temporary loss of the external ac or dc supply due to equipment failure or during transportation. MBF Frequency Distribution Modules provide outputs at 10, 5, 1, and 0.1 MHz.

PRODUCT LINE SUMMARY

Ball Efratom Division

Special Projects



NAVSTAR-GPS SATELLITE
RUBIDIUM OSCILLATOR

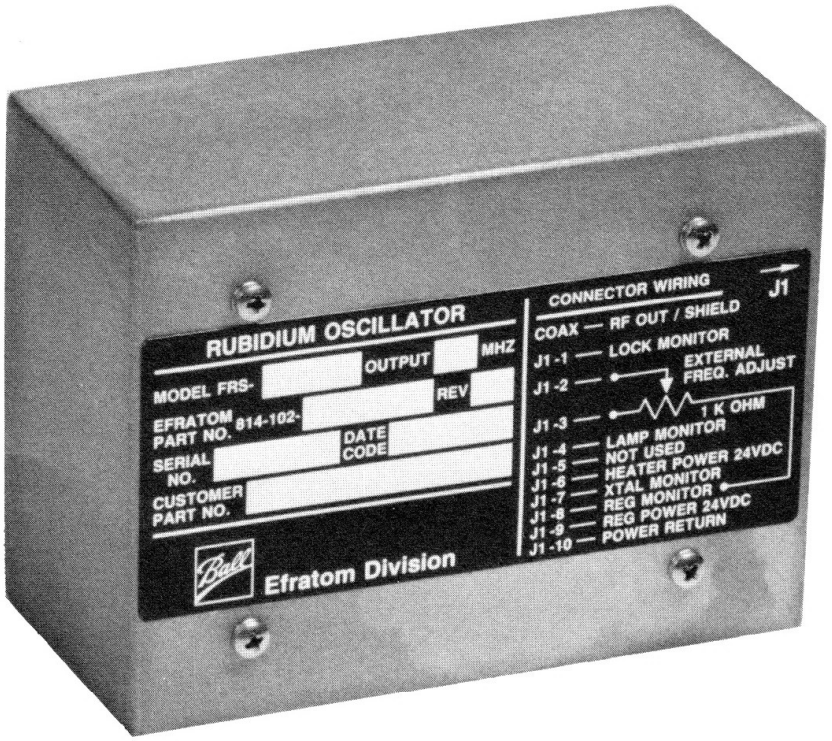
THE NAVSTAR GPS SATELLITE RUBIDIUM OSCILLATOR IS THE COMBINED EFFORT OF ROCKWELL INTERNATIONAL AND EFRATOM.

THE OSCILLATOR IS BUILT BY ROCKWELL TO THE BASIC EFRATOM MODEL FRK Rb DESIGN. EFRATOM DELIVERS THE PHYSICS PACKAGE PORTION ALONG WITH SEVERAL OTHER COMPONENTS USED IN THE UNIT.

THE BASIC SPECS ARE:

SIZE:	5"H x 7.5"W x 4.5"D
WEIGHT:	4.4kg (9.7 LBS)
POWER:	30W AT 26.5 Vdc
AGING:	~1 E-13/DAY
STABILITY:	~2 E-13 @ τ=10 ^{5}sec

Detailed Specification Sheets



FRS series Sub-miniature Commercial Rubidium Time Base Oscillator

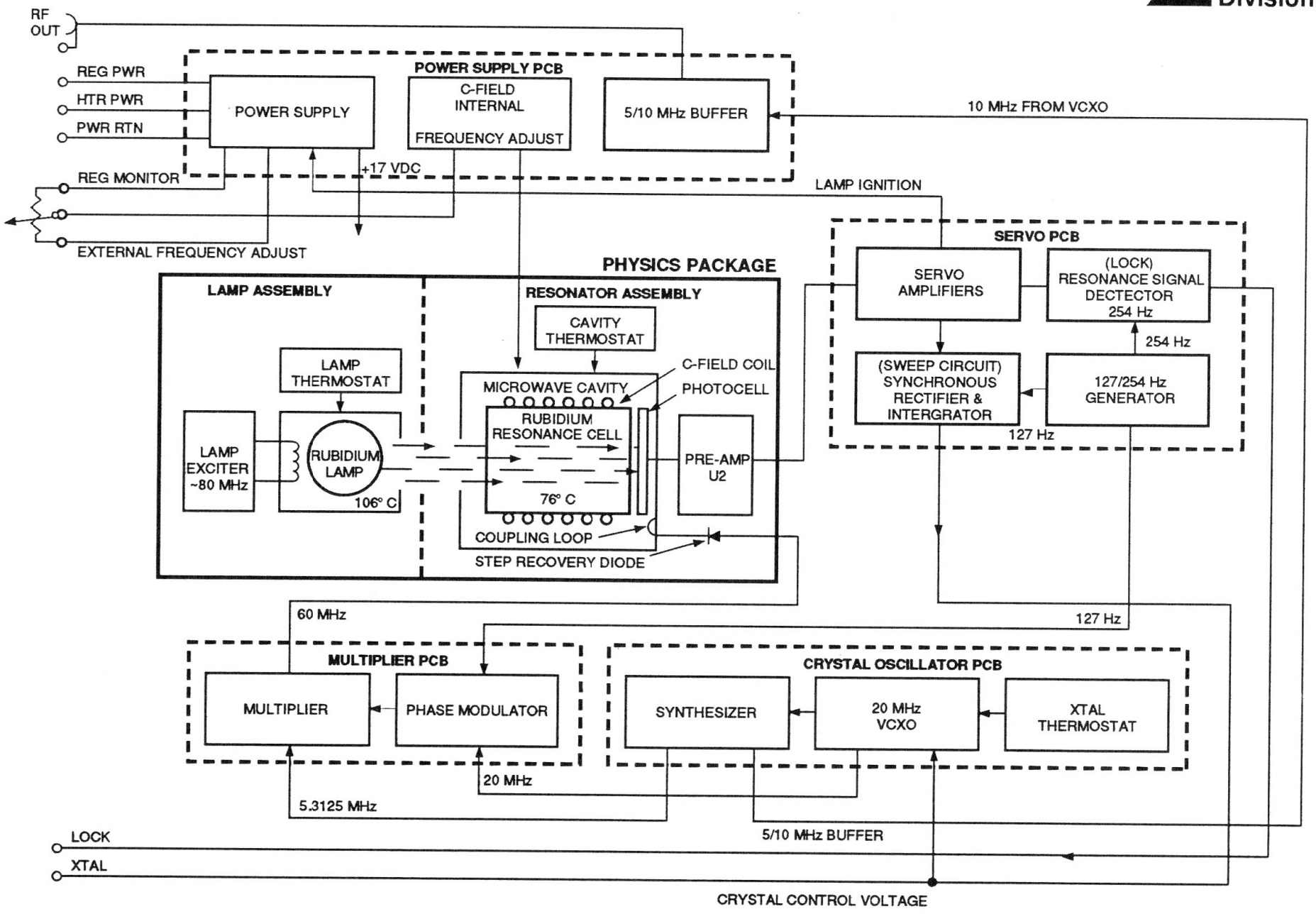
To our knowledge, this is the smallest, lowest cost general purpose rubidium atomic oscillator available. Model FRS-C is used as a frequency generator/time base in instruments, work stations, telephone networks, the GPS user equipment community and many other applications.

Model FRS-N is used when extended operating temperature range is required, such as ground and airborne mobile terminals.

Often the FRS replaces conventional high performance quartz OCXO oscillators, providing atomic precision at comparable cost.

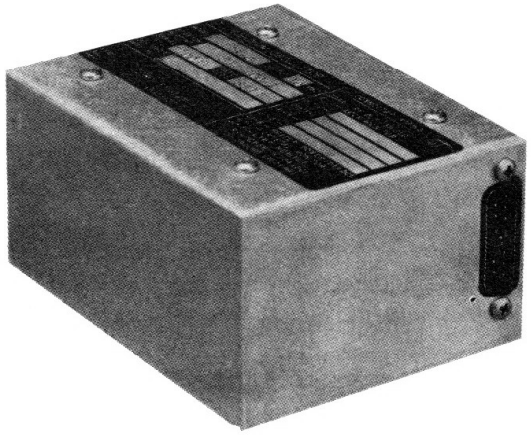
MODEL FRS BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

FRS-C Series Commercial Rubidium Time Base Oscillator



- For Time Base Applications
- Designed for Use in Instruments, Receivers, Test Equipment, and Networks
- Extremely Small 2 x 3 x 4 inches, 1.2 lbs.
- Frequency Accuracy of 1E-9/Year
- Low Power Consumption
- Low Cost
- Rf Outputs Available:

  5 MHz sine
  10 MHz sine
  10 MHz TTL
  2.048 MHz TTL

Description

The Model FRS-C is an ultra-stable miniature atomic oscillator designed for direct installation into instruments as well as the local oscillator and time base for systems and networks. The 10 MHz sinusoidal output provides excellent short and long-term stability for commercial and industrial environmental conditions. It has been designed to maximize performance in the smallest possible package at low cost.

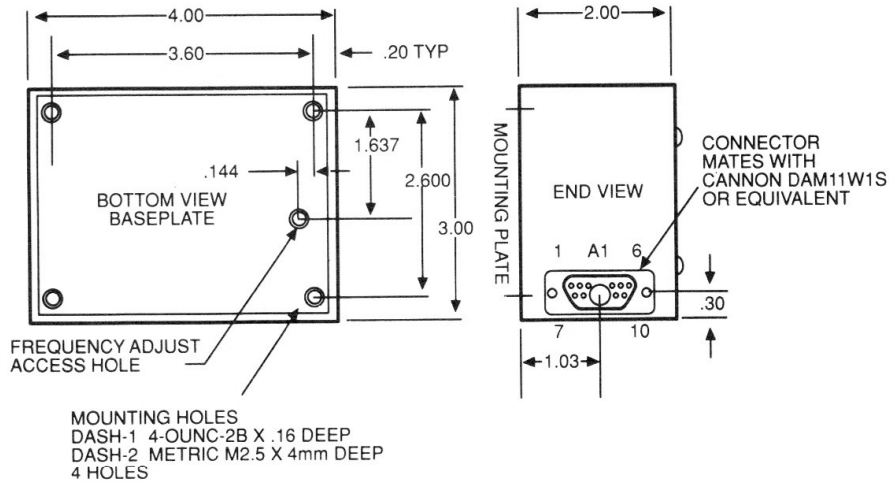
Components, instruments, and systems benefit from a stable time-base because it extends calibration time of the output frequency. In addition, the FRS is specifically designed to eliminate VCXO control voltage adjustment for at least 5 years. Central frequency and time-base concepts can tie together all instruments in a test station or network for coherent and synchronized measurements.

The small volume of 24 cubic inches and a weight of less than 1.2 lbs has been achieved by the application of new physical and technological concepts which include new advances in package design. The FRS-C closes the gap between today's most advanced quartz crystal oscillators and the more expensive high performance rubidium frequency standards.

Applications

Atomic oscillator precision is required for both time and frequency in a wide variety of applications. Among these are the user receivers and transceivers for radio navigation using OMEGA and NAVSTAR-GPS, mobile communications, control networks, systems, instruments, and telephone communication networks.

FRS OUTLINE DRAWING



CONNECTOR WIRING

PIN A1	RF OUTPUT COAX
J1 -1	LOCK MONITOR
J1 -2	EXT FREQ ADJ
J1 -3	
J1 -4	LAMP MONITOR
J1 -5	NOT USED
J1 -6	HEATER PWR +24VDC
J1 -7	XTAL MONITOR
J1 -8	REG MONITOR
J1 -9	REG POWER +24VDC
J1 -10	POWER RETURN

FRS-C Series Commercial Rubidium Time Base Oscillator (continued)

FIGURE 1 – PHASE NOISE

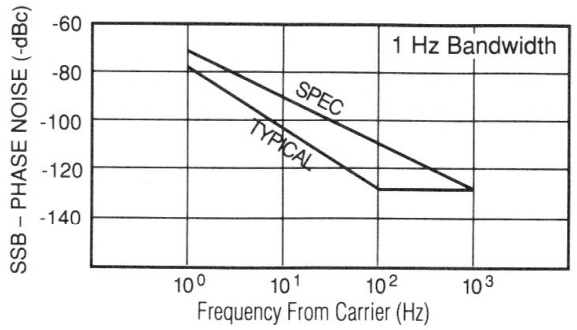
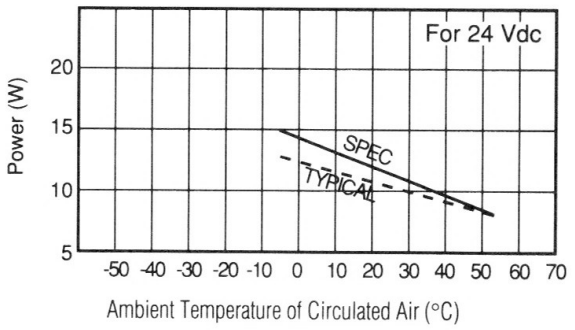


FIGURE 2 – POWER DISSIPATION



Electrical Performance

Output Frequencies/Waveform	10 MHz/sine, 5 MHz/sine 10 MHz/TTL, 2.048 MHz/TTL
Output Level/Load (ohms)	0.5 Vrms/50 (+30/–10% Vrms)
Bite Output	Rb Lock
No-Fault/Fault Logic Level	0/1 (TTL compatible)
Short-Term Stability (Note 1)	
1.0 Second (Allan Var.)	1E-10
10 Second (Allan Var.)	3.16E-11
100 Second (Allan Var.)	1E-11
1-Day Stability (25 ±3°C)	1E-10
Aging Per Month	5E-11(After 1 month of continuous operation)
Freq. Accuracy At Shipment	±5E-11 (25°C)
At One Year	1E-9/Year (Note 1)
Frequency Trim Range	±1E-9 Minimum
Setting Resolution	1E-11
Frequency Retrace	5E-11 (After 1 hr. pwr on @ 25°C & up to 24 hrs pwr off)
Phase Noise (Figure 1)(Note 2)	
1 Hz from carrier	-70 dBc/$\sqrt{\text{Hz}}$
100	-110 dBc/ $\overline{\text{Hz}}$
1000	-130 dBc/ $\overline{\text{Hz}}$
Harmonic/ Non-Harm Distortion	-40 dBc (sine)/-65 dBc
Input Voltage Range	22 to 30 Vdc
Power, Steady State	12 W @ 24 Vdc @ 25°C Base Plate (Figure 2)
At Turn On	2.0 A peak
Input Voltage Sensitivity	5E-11 (for ±10% Vdc)
Warm-Up Time	
Time To Lock @ 25°C	4 minutes
Minutes/Frequency @ 25°C	6 minutes/1E-9

Note 1: Includes: Aging, Freq. Offset Over Temp. Range, Setting Accuracy at Shipment, and 10% Input Voltage Change

Note 2: 5 and 10 MHz outputs only

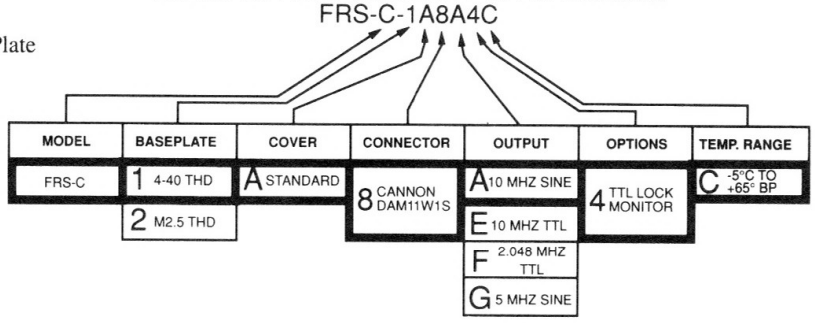
Environmental Performance

Operating Temp. Range	-5°C/+65°C (Base plate)
Freq. Offset Over Range	3E-10
Storage Temp (Non-Op)	–55°C to +85°C
Magnetic Field Sensitivity	4E-13/AM^{-1} (Worst case) (3E-11/gauss)
Altitude, Vibration, Shock	MIL-T-28800, Type III, Class 5
Relative Humidity	95%

Physical

Weight/Volume	
Lbs./cubic inches	1.2 / 24
kg/cubic cm	0.55 / 395
Size (inches, h/w/d)	2.0 / 3.0 / 4.0
(cm, h/w/d/)	5.1 / 7.6 / 10.2
Base Plate Mounting Thread	4-40 (Std) m 2.5 (Option)
Connector	Mate with Cannon series DAM11W1S or equivalent
Reverse Polarity Protected	Yes
Warranty	1 year

EXAMPLE PART NUMBER FOR ORDERING
FRS-C-1A8A4C



Note: Heavy line boxes constitute standard configuration

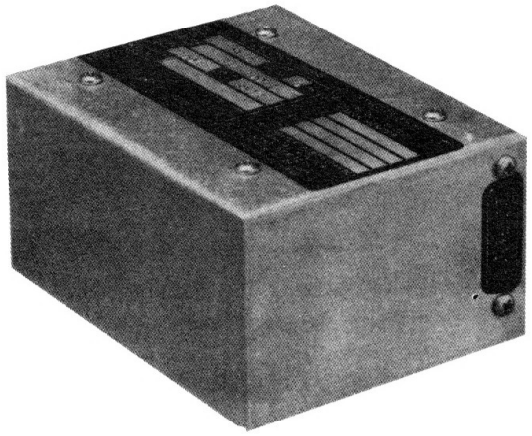
Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

3/91

Ball Efratom Division

FRS-N Miniature Commercial Rubidium Oscillator



- For Navigation, Communications and Laboratory Applications
- Wide Operating Temp Range -55°C to +65°C Base Plate
- Extremely Small 2 x 3 x 4 inches, 1.2 lbs.
- Frequency Accuracy of 1E-9/Year
- Low Power Consumption
- Rf Outputs Available:
  - 5 MHz sine
  - 10 MHz sine

Description

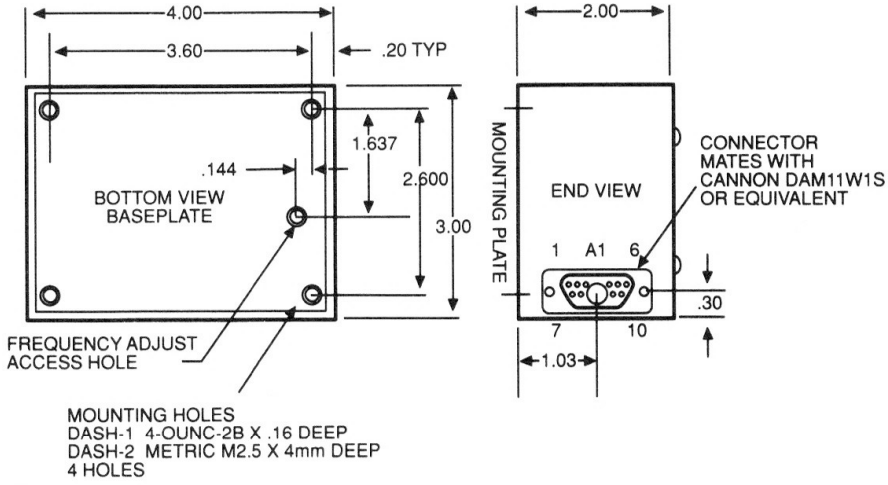
The Model FRS-N is an ultra-stable miniature atomic oscillator designed for direct installation as a component in equipment and systems and laboratory frequency systems as a local oscillator and time base. The 10 MHz sinusoidal output provides excellent short- and long-term stability over a wide range of environmental conditions.

The small volume is achieved by the application of new physical and technological concepts which include new advances in package design. The FRS-N closes the gap between today's most advanced quartz crystal oscillators and larger, more expensive high performance rubidium and cesium frequency standards. The FRS has been specifically designed to eliminate VCXO control voltage adjustments for at least 5 years.

Applications

Atomic oscillator precision is required for both time and frequency in a wide variety of applications, including: radio navigation using Omega/VLF, Loran-C and satellite transmissions (GPS-TRANSIT-GOES); geophysical survey positioning systems; satellite tracking and guidance control; communications systems employing PCM and spread spectrum techniques; standard time and time interval generation and transfer. The FRS-N is the most economical choice where a combination of excellent spectral purity, short-term and long-term stability are essential. It contributes to simplification of system design because of low frequency aging which extends the period of time needed between calibration or synchronization. This rugged and compact rubidium oscillator is especially advantageous when utilized in mobile/transportable applications where fast warm-up, low power consumption, and small volume are required.

FRS OUTLINE DRAWING



CONNECTOR WIRING

PIN A1	RF OUTPUT COAX
J1 -1	LOCK MONITOR
J1 -2	EXT FREQ ADJ
J1 -3	
J1 -4	LAMP MONITOR
J1 -5	NOT USED
J1 -6	HEATER PWR +24VDC
J1 -7	XTAL MONITOR
J1 -8	REG MONITOR
J1 -9	REG POWER +24VDC
J1 -10	POWER RETURN

FRS-N Miniature Commercial Rubidium Oscillator (continued)

FIGURE 1 – PHASE NOISE

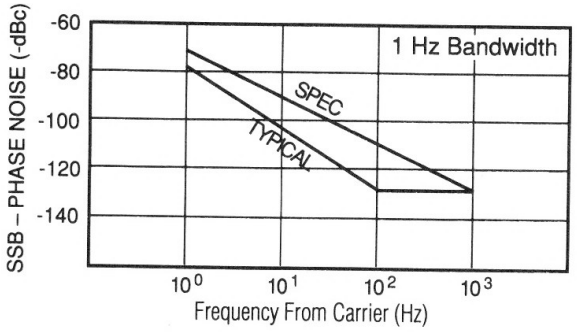
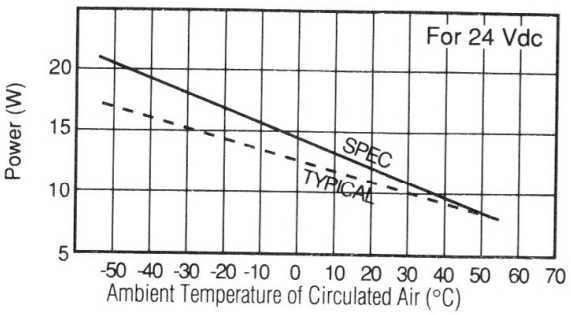


FIGURE 2 – POWER DISSIPATION



Electrical Performance

Output Frequencies/Waveform	10 MHz/sine, 5 MHz/sine
Output Level/Load (ohms)	0.5 Vrms/50 (+30/–10% Vrms)
Bite Output	Rb Lock
No-Fault/Fault Logic Level	0/1 (TTL compatible)
Short-Term Stability	
1.0 Second (Allan Var.)	5E-11
10 Second (Allan Var.)	1.58E-11
100 Second (Allan Var.)	5E-12
1-Day Stability (25 ±5°C)	1E-10
Aging Per Month	5E-11(After 1 month of continuous operation.)
Drift After One Year	5E-10, 2E-10/yr thereafter
Freq. Accuracy At Shipment	±5E-11 (25°C)
At One Year	1E-9/year (Note 1)
Frequency Trim Range	±1E-9 minimum
Setting Resolution	1E-11
Frequency Retrace	5E-11 (After 1 hr. pwr on @ 25°C & up to 24 hrs pwr off)
Phase Noise (Figure 1)	
1 Hz from carrier	-70 dBc/$\sqrt{\text{Hz}}$
100	-110 dBc/ $\overline{\text{Hz}}$
1000	-130 dBc/ $\overline{\text{Hz}}$
Harmonic/ Non-Harm Distortion	-40 dBc/-65 dBc
Input Voltage Range	24 Vdc nominal (22-29.5 Vdc) (RTCA DO-160B, Cat A for voltage levels & spikes, CAT.B for ripple)
Power, Steady State	12 W @ 24 Vdc @ 25°C Base Plate (Figure 2)
At Turn On	2.0 A peak
Steady State	21 W @ 24 Vdc (-55°C circulated air, base plate ~(-)45°C)
Input Voltage Sensitivity	5E-11 (for ±10% Vdc)
Warm-Up Time	
Time To Lock @ 25°C	4 minutes
@ -55°C	8 minutes
Minutes/Frequency @ 25°C	6 minutes/1E-9

Note 1: Includes: Aging, Freq. Offset Over Temp. Range, Setting Accuracy at Shipment, and 10% Input Voltage Change

Environmental Performance

	Per RTCA DO-160B
Operating Temp. Range	-55°C/+65°C (Base plate)
Freq. Offset Over Range	5E-10
Storage Temp (Non-Op)	–55°C to +85°C
Temperature Variations	CAT. B (5°C/minute minimum)
Altitude	Ops to 70,000 ft. (21,300m)
Temperature/Altitude	CAT.E1
Magnetic Field Sensitivity	4E-13/Am^{-1} (Worst case) (3E-11/gauss), CAT. A
Vibration (sine)	Curves M, N, O 1.5 G to 500 Hz 1.0 G to 1000 Hz
Shock (Operational)	6 G, 11 ms
Crash Safety	12 G, 11 ms
Explosion	CAT. E
Relative Humidity	CAT. A, 95%
Conducted Susceptibility	Af CAT. B (power input) Rf CAT. A
Induced Sig. Susceptibility	CAT. A
Emission of Radio Frequency	CAT. A

Physical

Weight/Volume	
Lbs./cubic inches	1.2 / 24
kg/cubic cm	0.55 / 395
Size (inches, h/w/d)	2.0 / 3.0 / 4.0
(cm, h/w/d)	5.1 / 7.6 / 10.2
Base Plate Mounting Thread	4-40 (std) m 2.5 (option)
Connector	Mate with Cannon series DAM11W1S or equivalent
Reverse Polarity Protected	Yes
Warranty	1 year

EXAMPLE PART NUMBER FOR ORDERING
FRS-N-1A8A4B

MODEL	BASEPLATE	COVER	CONNECTOR	OUTPUT	OPTIONS	TEMP. RANGE
FRS-N	1 4-40 THD 2 M2.5 THD	A STANDARD	8 CANNON DAM11W1S	A 10 MHZ SINE E 10 MHZ TTL G 5 MHZ SINE	4 TTL LOCK MONITOR	B -55°C TO +65 BP C -5°C TO +65° BP

Note: Heavy line boxes constitute standard configuration

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

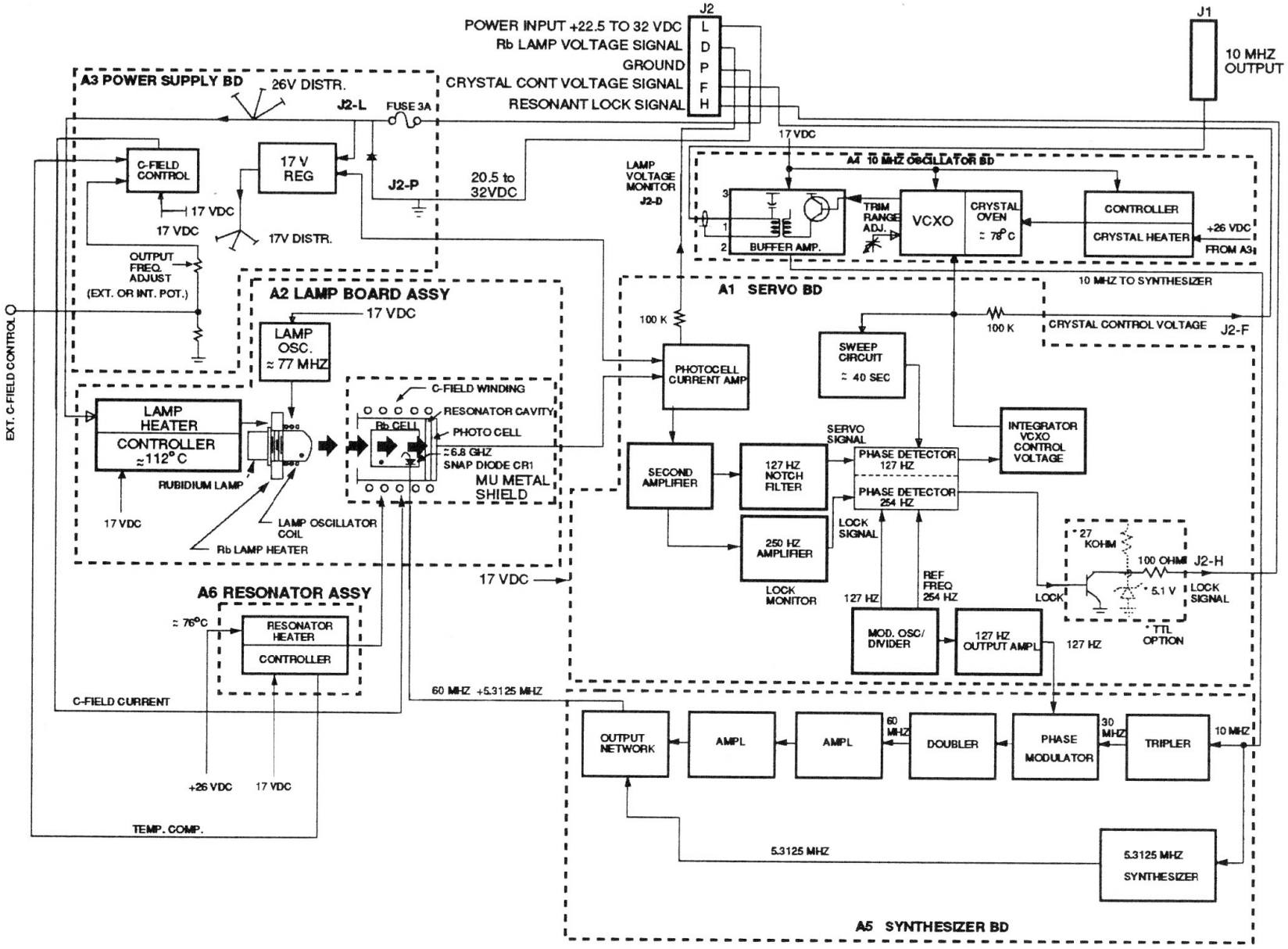
FRK Series Miniature Commercial High Performance Rubidium Oscillators

This unit forms the basis for the high performance rubidium oscillator technology. It is a general purpose oscillator used in almost every facet of commercial and military nav/com systems. It would normally be used when higher than FRS performance is needed for aging, phase noise and short term stability.

This unit is also the principal frequency generator in our MFS-Modular Frequency & Time Systems product line.

MODEL FRK BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

FRK Series Commercial Rubidium Oscillator

- High Performance Atomic- Resonance-Controlled Oscillator
- Extremely Compact and Lightweight
- High Spectral Purity/Low Phase Noise
- Fast Warm-Up
- Low Power Consumption
- Options Available:
  - H (Low Aging)
  - LN (Low Noise)
  - (–) 55° C. Temp. Ops
  - (or any combination)

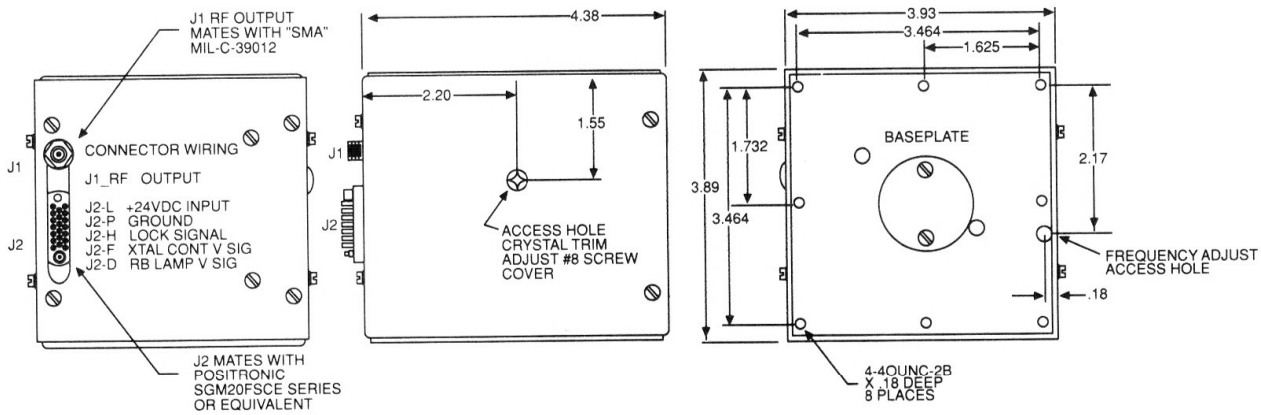
Description

The Models FRK-H and -L are ultra-stable miniature atomic oscillators designed for direct installation as components in equipment and systems as well as for use as laboratory frequency standards, local oscillators and time bases. The 10 MHz sinusoidal output provides excellent short and long-term stability over a wide range of environmental conditions. For multiplication to higher frequency ranges, a 5 or 10 MHz low phase noise option with state-of-the-art performance is offered.

The small volume of approximately 1 liter and a weight of less than 1.3 kg (2.9 lbs.) has been achieved by the application of physical and technological concepts which include advances in package design. The FRK-H and -L ultra-stable oscillators close the gap between today's most advanced quartz crystal oscillators and the more expensive high performance cesium frequency standards.

Applications

Atomic oscillator precision is required for both time and frequency in a wide variety of applications, including: radio navigation using Omega/VLF, Loran-C, and satellite transmissions (GPS-TRANSIT-GOES); geophysical survey positioning systems; satellite tracking and guidance control; communications systems employing PCM and spread spectrum techniques; standard time and time interval generation and transfer. Both models ensure atomic oscillator precision and high reliability. They are the most economical choice where a combination of excellent spectral purity, short-term and long-term stability are essential. They contribute to simplification of system design because of the excellent frequency stability which extends the period of time needed between calibration or synchronization. These rugged and compact rubidium oscillators are especially advantageous when utilized in mobile/transportable applications where fast warm-up and low power consumption are required.



FRK Series Commercial Rubidium Oscillator (continued)

FIGURE 1 – PHASE NOISE

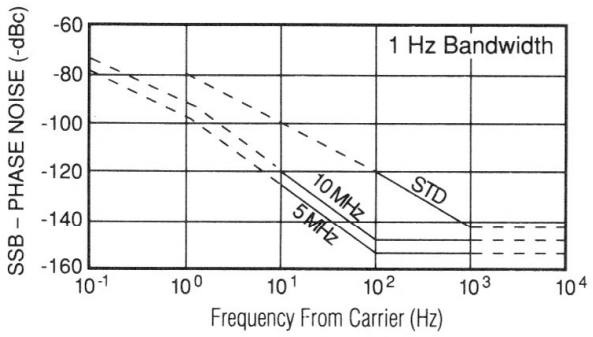
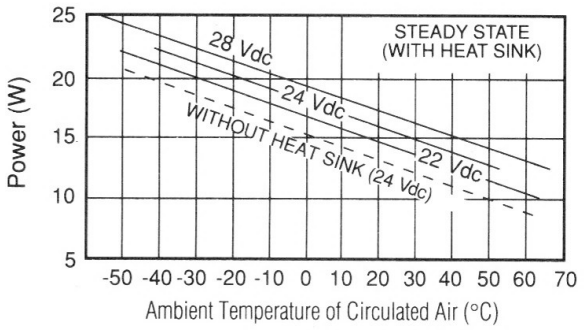


FIGURE 2 – POWER DISSIPATION



Electrical Performance

Output/Frequency/Waveform	10 MHz/sine
Low Noise Option	5 or 10 MHz (FRK-LN)
Output Level/Load (ohms)	0.5 Vrms / 50 (+30/–10% Vrms) 1.0 Vrms / 50 (±10% Vrms)(FRK-LN)
Bite Output	Rb Lock
No-Fault/Fault Logic Level	0/1 (open collector)
Aging Per Month	4E-11
Aging Option	1E-11 (FRK-H)
Short-Term Stability	
1.0 Second (Allan Var.)	3E-11 1E-11 (FRK-H)
10 Second (Allan Var.)	1E-11 3.16E-12 (FRK-H)
100 Second (Allan Var.)	3E-12 1E-12 (FRK-H)
Freq. Accuracy At Shipment	±5E-11 (25°C)
Frequency Trim Range	2E-9
Setting Resolution	1E-11
Frequency Retrace	2E-11 (After 1 hr. pwr on @ 25°C & up to 48 hrs pwr off)

Phase Noise (Figure 1)

-dBc/√ Hz	FRK Std	FRK-LN 10 MHz	FRK-LN 5 MHz
10 Hz from carrier		120	125
100 Hz	120	147	155
1000 Hz	145	147	155

Harmonic/ Non-Harm Distortion	-20 dBc/-70 dBc
Input Voltage Range	22 to 32 Vdc
Power, Steady State	@25°C 13 W @ 24 Vdc (Figure 2)
At turn on @25°C	1.8 A peak
Input Voltage Sensitivity	1E-11 (for ±10% Vdc)
Warm-Up Time	
Minutes/Frequency @ 25°C	10/2E-10

Environmental Performance

Operating Temp. Range	-25°C/+65°C (Base plate)
Freq. Offset Over Range	3E-10 1E-10 (FRK-H)
Temp. Option	-55°C/+65°C (Base plate) 6E-10 4E-10 (FRK-H)
Storage Temp (Non-Op)	–55°C to +75°C
Magnetic Field Sensitivity	4E-13/Am^{-1} (Worst case) (3E-11/gauss)
Pressure Sensitivity for Sea Level to 40,000 ft.	-7E-11, (<1E-13/mbar)
Vibration	MIL-STD-810C, Method 514.2 Procedure 1, Curve B
Shock	MIL-STD-810C, Method 516.2 Procedure 1
Relative Humidity	95% (MIL-T-5422F)
Approx. MTBF, Stationary	50,000 hours

Physical

Weight/Volume	
Lbs./cubic inches	2.9 / 67
Size (inches, h/w/d)	3.9 / 3.9 / 4.4
Base Plate Mounting Thread	4-40 (std) m 2.5 (Option)
Connectors	J1 rf output mates with "SMA" MIL-C-39012 J2 mates with Positronic SGM20FSCE series or equivalent
Reverse Polarity Protected	Yes
Warranty	1 year

EXAMPLE PART NUMBER FRK-L-1A1A1A FOR ODERING

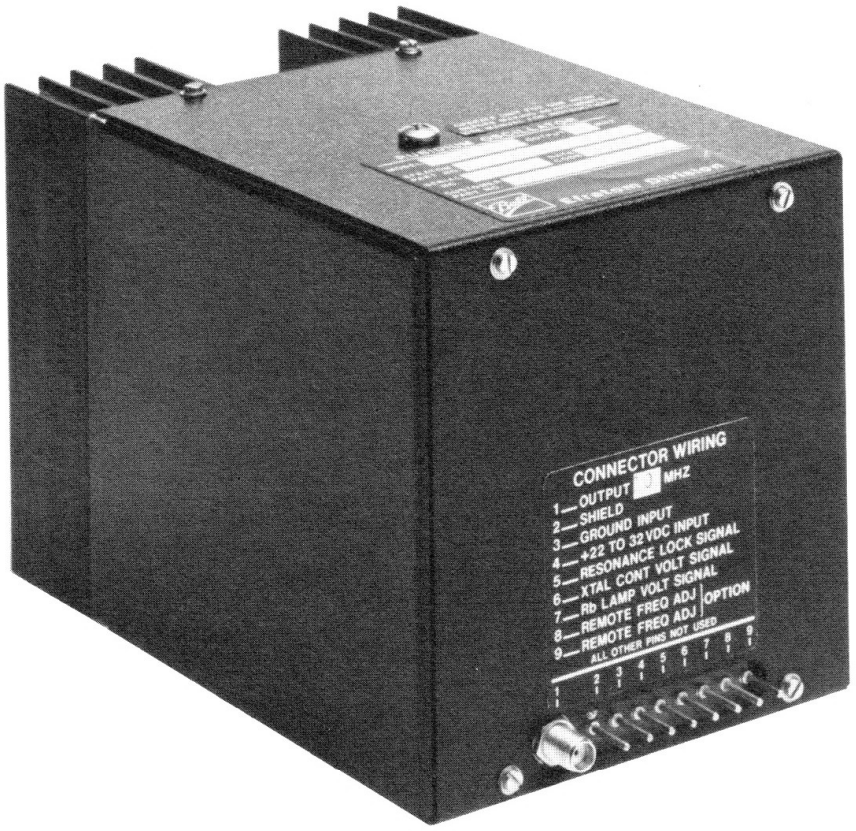
MODEL	BASEPLATE	COVER	CONNECTOR	OUTPUT	OPTIONS	TEMP. RANGE
FRK-L 10 MHZ ONLY	1 4-40 THD	A STANDARD MU-METAL	1 WIN-CHESTER AND COAX	A 10 MHZ SINE	1 INTERNAL POT FREQ. ADJ.	A STANDARD -25°C TO +65 BP
FRK-H 10 MHZ ONLY	2 M2.5 THD			B 5 MHZ LN		
FRK-LLN 5 OR 10 MHZ				D 10 MHZ LN		B EXTENDED -55°C TO +65 BP
FRK-HLN 5 OR 10 MHZ						

Note: Heavy line boxes constitute standard configuration

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

3/91

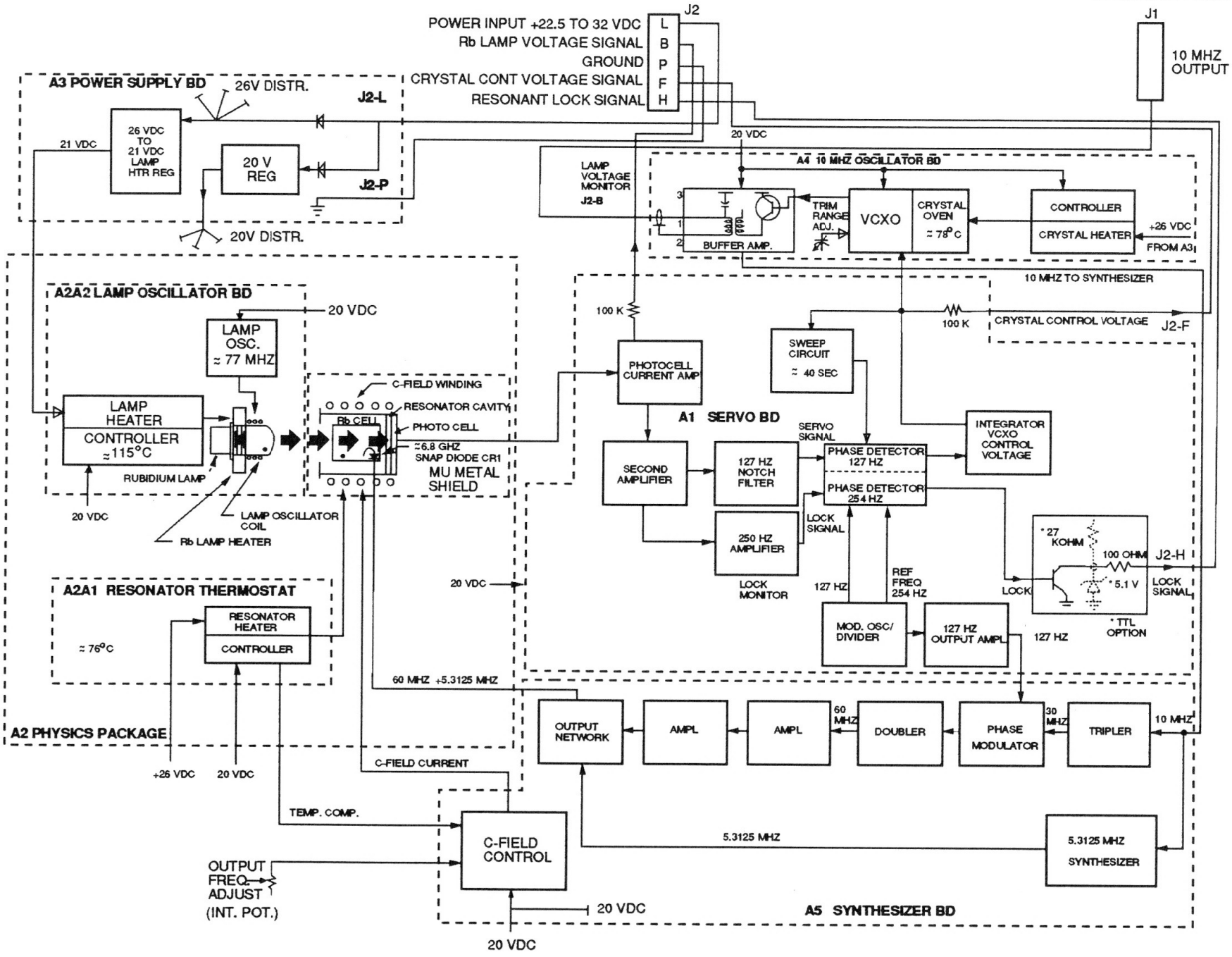


M100 Series Miniature Military High Performance Rubidium Oscillator

This unit is a MIL-E-5400, Class I, version of the basic rubidium oscillator technology, fully tested and mil qualified. This unit is applied when stringent vibration, shock, radiation hardening and wide temperature operations are demanded. Most of the world's tactical military communications and navigation use this unit.

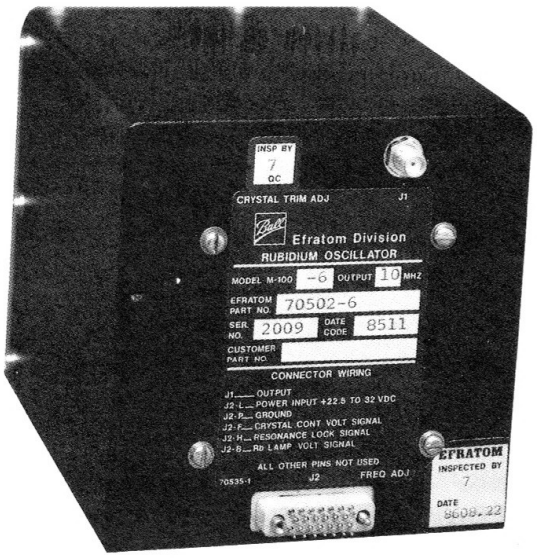
MODEL M100 BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

M-100 Series Military Rubidium Oscillator



- MIL-E-5400 Spec Design for Tactical Environments
- Qualified and Field Tested for Army, Navy, and USAF Programs
- Fully Radiation Hardened and Chamber Tested
- Small, Rugged, Lightweight
- Bite Monitoring Outputs
- Options Available:

  Low Aging, Low Noise, Fast Warm-up, and Higher Temp Range

Description

The M-100 is considered a standard for Military Tactical Rubidium Oscillator applications. The unit has been qualified by the Army, Navy and USAF and presently serves a variety of military time/frequency systems.

The Oscillator has an exceptionally stable 10 MHz output with a long term drift of about 2E-10/year. The unit's dimensions are approx. 4" x 4" x 5" with a weight of less than 4 lbs. All parts are QPL Level-B, or QPL-B equivalent screen, conservatively derated to assure reliable operation. The M-100 requires an input voltage of 22.5 to 32 Vdc. The short-term stability and phase noise specs are among the best available today.

In order to assure the highest degree of flexibility in the military systems design, various M-100 options are available which serve to optimize performance and application. These options are detailed in the specification section but are briefly described below:

M-100	This is the standard M-100 military unit.
M-100-H	Low aging option of 1E-11/mo.
M-100-FW	Fast warm-up option of 5 minutes at 25°C
M-100-LN	5MHz low phase noise option of -155dB @ 300 Hz
M-100-HC	High-temp environment option of 75°C baseplate

Or combinations of the above options

Applications

In today's sophisticated electronic systems, atomic precision must often be maintained for both frequency and time. For this reason, the M-100 fills approximately 2000 time/frequency slots in typical applications listed below:

- Radio Navigation using Omega-VLF, Loran-C, and Navstar-GPS
- Relative Navigation and Positioning Systems for Tactical Theater
- Tropposcatter Communication Terminals
- Mil-Satcom Terminals
- Spread Spectrum Communication Systems
- HI-AJ/Crypto Tactical Terminals
- Nodal-Switch Communications Terminals
- Time and Time Interval and Time Transfer Systems.

...and many other applications too numerous to list.

The outstanding frequency stability of the M-100 allows simplification of system design because of the extended periods of time between calibration or synchronization cycles. This rugged and compact rubidium oscillator is especially useful in mobile, ground and airborne applications where fast warm-up, low-power consumption and excellent stability are needed in a hostile environment.

M-100 Series Military Rubidium Oscillator (continued)

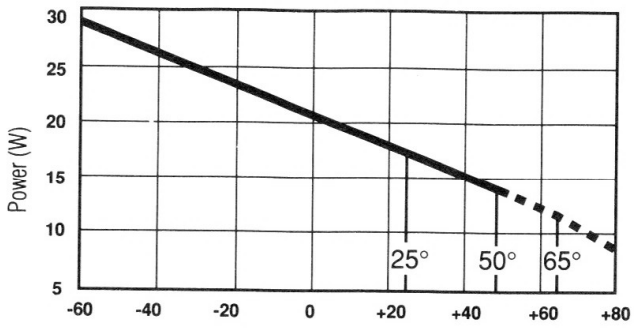
Electrical Performance

Output	10 MHz sine 0.5, +30%, -10% Vrms into 50 ohms, floating ground, frequency set to 10 MHz ±5E-11 at shipment
M-100-LN (Low Noise Option)	5 MHz, 1.0 Vrms, ±10%
Bite Output	Rb Lock
No-Fault/Fault Logic Level	0/1 (open collector)
Input Power	After warm-up, 18 W at 26 Vdc and 25°C ambient (See Figure 1.)
Input Voltage	22.5 to 32 Vdc, MIL-STD-704 (See Figure 6.)
Warm-up	≤10 mins to reach 2E-10 at +25°C ambient, ~2.0 A peak current
	≤15 mins. to reach 2E-10 at -55°C ambient, ~2.2 A peak current (See Figures 2 & 3).
M-100-FW (Fast warm-up option)	≤5 mins. to reach 2E-10 at +25°C ambient, ~3.6 A peak current (See Figure 3.)
Input Voltage Sensitivity	<1E-11 for ±10% input voltage change (within input power limits stated)
Aging	6E-11 for the first month after 14 days of continuous operation. 3.6E-10 for the first year. 2E-10 per year starting with 2nd year.
M-100-H (Low aging option)	1E-11
Short-Term Stability (Allan Variance)	3E-11, τ 1 sec
	1E-11, τ 10 sec
	3E-12, τ 100 sec (See Figure 4.)
M-100-H (Low aging option)	1E-11, τ 1 sec
	3.16E-12, τ 10 sec
	1E-12, τ 100 sec (See Figure 4.)
Phase Noise	>130 dB 100 Hz
	>140 dB 1 kHz (See Figure 5.)
M-100-H (Low phase noise option)	>155 dB 300 Hz (See Figure 5.)
Harmonic/ Non-Harmonics	-30 dBc/80 dBc
Adjustment Range	3E-9
Settability	1E-11 (after 1 hr. pwr on)
Retrace	2E-11, @ 25°C & up to 48 hrs pwr off

Physical

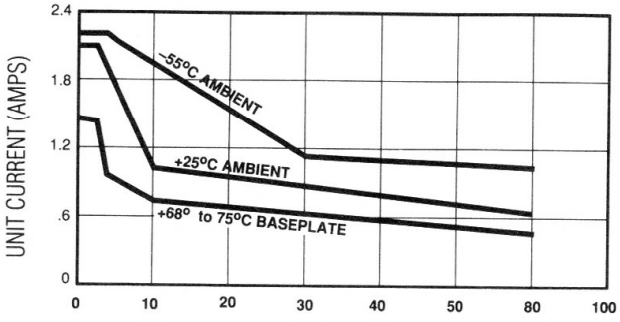
Size	3.94 x 3.90 x 4.81 inches (See Figure 8.)
Weight	4 lbs max.; with std heat sink 4.5 lbs.
Electrical Protection	Power leads protected against reversed polarity
	Output protected against shorts

Specifications



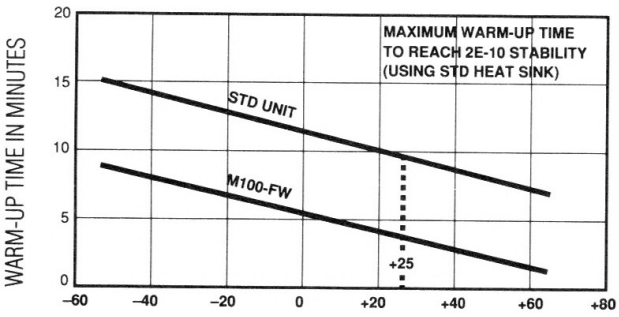
Amb. Temp. of Circulated Air (°C)

Figure 1 – Input Power



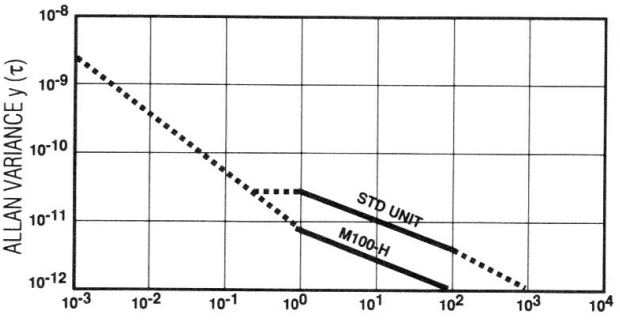
Time After "Turn On" in Minutes

Figure 2 – Warm-Up Current



Amb. Temp. of Circulated Air (°C)

Figure 3 – Warm-Up Time



Sampling Time (τ) In Seconds

Figure 4 – Short Term Stability

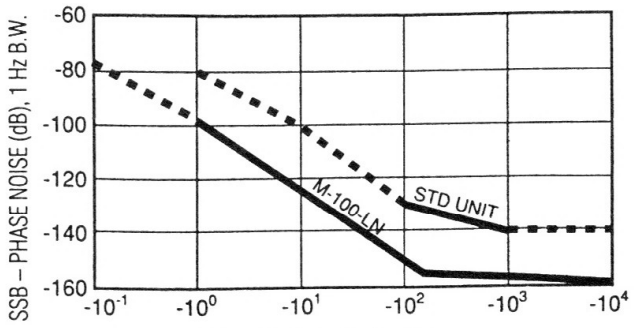


Figure 5 – Phase Noise

SPEC	NORMAL	ABNORM	DROPOUT	TRANSIENT	RIPPLE
704A CAT B	24 - 28.5 VDC	22.5 - 30 VDC	7 SEC	600V, 10 s 80V, 50 ms	2VP-P
704C	22-29 VDC	20 - 31.5 VDC	5 SEC	50V, 45 MS	1.5VP-P
M100 COMPATIBILITY					
ELEC. BUS	22.5 - 32 VDC	20.5 - 32 VDC	100 s	50V, 50 ms	YES
HTR BUS	22.5 - 32 VDC	20.5 - 32 VDC	10 SEC	50V, 50 ms	YES
COM-PLIANCE	YES	704A YES 704C	ELEC BUS - NO HTR BUS - YES	704A NO 704C YES	YES

Figure 6 – MIL-STD-704 Electrical Power Spec Compatibility

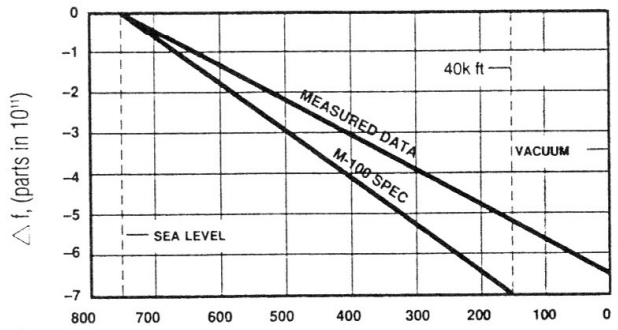
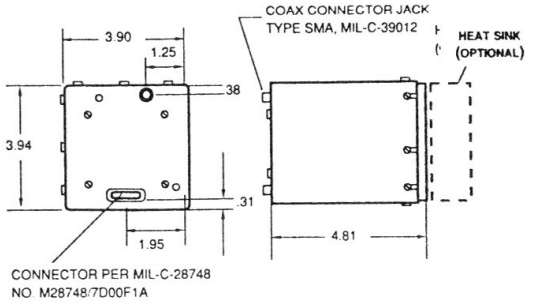


Figure 7 – Pressure (mm Hg)



Mating Connectors Supplied With Unit

Figure 8 – Dimensions

Environmental Performance

Operating Temperature	<3E-10 from -55° (ambient) to +68°C (baseplate). Meets MIL-E-5400, Class I; Parts in 10^9 offset at 71°C (baseplate)
M-100-HC (High Temp. Option)	<3E-10 from -55° (ambient) to +75°C (baseplate) exceeds MIL-E-5400, Class I
Storage Temperature	–62°C to +85°C (MIL-E-5400, Class I)
Magnetic Field	<3E-13/AM^{-1} worst case orientation; (2.4E-11/gauss)
Pressure	<7E-11 from sea level to 12,000m (40,000 ft) <1E-13/mbar (See Figure 7.)
Acceleration	<4E-12/g (worst orientation)
Vibration	0.02 g^2/Hz, 20 to 50 Hz; 0.001 g^2/Hz at 500 Hz. Allan Variance ~1E-10 for τ = 1 sec; <0.2 µsec/hr time error Improved performance available
Shock	<1E-7 momentary offset (worst orientation) with shock of 50g, 1/2 sine, 11 msec duration
Radiation	(Report available)
Dose Rate: 6.5E+10 Rads/Sec	Recovery to <5E-11 in less than 3 sec
Total Dose: 1E+4	Offset <5E-11 with dose applied in 3 hrs.
Neutron Fluence: ~1E + 13 neut./cm^2	Offset <1E-10 with dose applied in ~3 hrs.
EMI (Report available)	MIL-STD 461A, Notice 3 CE01, 02, 03, 04 RE02, 0.014 to 1000 MHz CS01, 0.03 to 50 kHz CS02, 0.05 to 400 kHz CS06 Spike RS01, Mag. Field, 0.03 to 30 kHz RS02, Mag. Induction RS03, Electric Field
Humidity	94% Relative Humidity
Reliability (Report available)	Level-B QPL or equivalent screened parts, per MIL HDBK-217D >81,000 hrs, ground, stationary environment, at 50°C air.
Warranty	1 year Extended warranties available.

M-100 Series Military Rubidium Oscillator (continued)

Acceptance Test (Each Unit)

PRE-ATP 0.1 g^2/Hz, 20 to 500 Hz
Vibration (6.9 grms) in optical axis
Complete Functional Test

ATP

Warm-up and lock test

Output level test

Short-term stability test

Frequency vs. temperature test
(-55°C Amb. to +68°C baseplate for M-100; +75°C baseplate)

Trim range test

Temperature cycling (non-ops)
(-55°C to +70°C amb., 1-hour dwell, 10 cycles)

Burn-in and long-term drift test (7 day minimum at amb. temp.)

Harmonic/Non-harmonic distortion

Phase Noise for M-100-LN

Qualification Test

Vibration - Sine Sine, Test #1 (non-ops)
MIL-STD-202E, Method 204C, Test Condition-A (10g peak 0.3 inch double ampl; 10 Hz to 200 Hz; 12 cycles. Three axis, total of 36 times)
Sine, Test #2 (non-ops)
(10 g peak, 0.005 inch double ampl; 200 Hz to 500 Hz 1-cycle, 3 axes, total of 3 times)

Vibration - Random Random Test #3 (operational)
0.02 g^2/Hz, 20 to 50 Hz falling linearly to 0.001 g^2/Hz at 500 Hz (vertical plane only)

Shock Shock Test #1 (non-ops)
MIL-STD-202E Method 213B, Test Condition-J (30 g peak 11 msec, 1/2 sine, 6.8 ft/sec, 3 shocks, 3 axis, 18 shocks)
Shock Test #2 (non-ops)
(10 g peak, 16 msec, 1/2 sine, 3.23 ft/sec, 4000 shocks)

Altitude MIL-STD-810C Method 500, Procedure I (Expanded to a soak of 15,000 m (50,000 ft); then 3,000 m (10,000 ft) and operate unit; return to ambient non-operating)

Hi-Temp MIL-STD-810C, Method 501, Procedure II (Expanded to 49°C, 68°C ambient, 40°C, three 12-hour cycles, non-ops; stabilized 68°C operational test)

Lo-Temp MIL-STD-810C, Method 502, Procedure I (Soak at -60°C ambient or -18°C baseplate, whichever is colder; then 40°C ambient; operate during last 2 hours)

Humidity MIL-STD-810C, Method 507.1, Procedure II modified (Dry at -54°C, soak at +23°C ambient, 50% humidity; then cycle with dwells between 0°C, 27°C and +49°C total of five 48-hour cycles at 100% humidity, operate unit once every 24 hours)

Operation

The M-100 output signal is derived from a 10 MHz voltage-controlled crystal oscillator (VCXO), whose frequency is locked to an atomic frequency reference. The atomic frequency reference is the 6.834 GHz ground-state hyperfine transition of ^{87}Rb (rubidium). The rubidium atoms that provide the atomic frequency reference are contained within a resonance cell in a resonator assembly. The VCXO is locked to the rubidium resonant frequency (f_{Rb}), at approximately 6.8 GHz, in the following manner. A microwave signal near f_{Rb} is synthesized from the 10 MHz VCXO output and used to excite the rubidium atoms contained within a microwave cavity. The frequency synthesis scheme is designed so that the VCXO frequency is exactly 10 MHz when the microwave frequency is exactly equal to f_{Rb}. The frequency of the signal applied to the microwave cavity can be maintained equal to f_{Rb} by generating an error signal when the microwave frequency differs from f_{Rb} and using this error signal to servo the VCXO via its control voltage.

The error signal is generated by the physics package which consists of the lamp board and the resonator assemblies. Light from the rubidium lamp is generated by an rf excited plasma discharge and passes into the resonator assembly where it interacts with the rubidium atoms contained therein. Some of this light strikes the photocell inside the resonator assembly. When the applied microwave frequency is equal to f_{Rb} the rubidium atoms resonate with the microwave field in the cavity. This causes the light reaching the photocell to decrease. (The reason for this involves a detailed consideration of the physics of rubidium atoms interacting simultaneously with light and microwave radiation). A microwave modulation scheme is used to continuously minimize the photocell current thereby locking the VCXO to f_{Rb}.

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

3/91

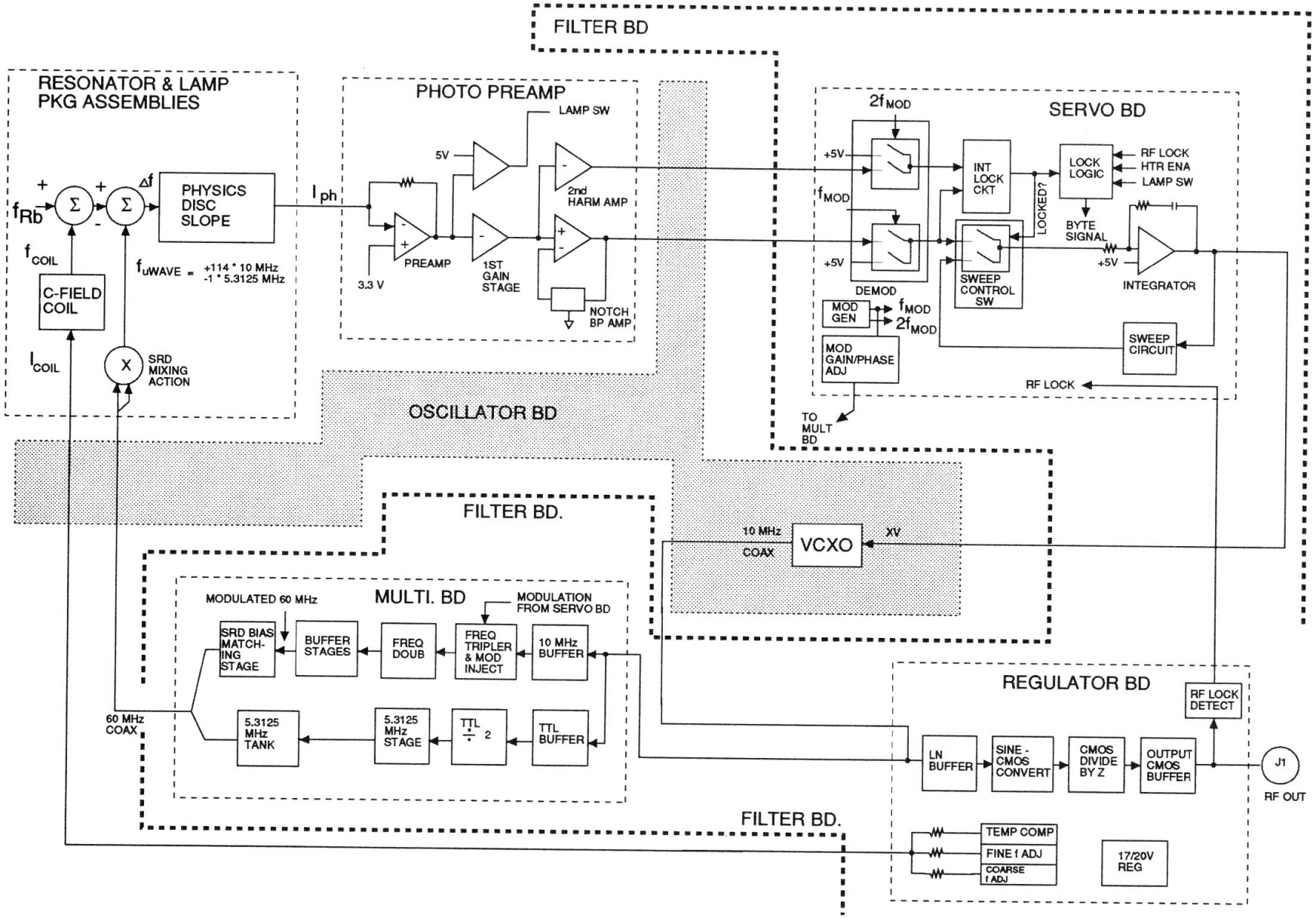
M3000 series Sub-miniature Military Tactical Rubidium Oscillator

This unit is a MIL-E-5400, Class II high performance rubidium oscillator and may be the world's standard in performance in stringent tactical environments. The M3000 would normally be used when higher than M100 performance is needed in (a) extended temperature range and 98°C emergency operations, (b) vibration vs. phase noise to 2000 Hz, (c) radiation hardness at a higher level (d) fast warmup and (e) smaller size.

MODEL M3000 BLOCK DIAGRAM

Ball Efratom Division

M3000 BLOCK DIAGRAM, SIMPLIFIED (IGNORING HEATERS)



Ball Efratom Division

M-3000 Series Military Rubidium Oscillator

- Meets MIL-E-5400, Class II
- 98°C Emergency Operations
- Low Phase Noise, Under Vibration (low g-sensitivity crystal)
- Fast Warm-Up
- Fully Radiation Hardened & Tested
- BITE Monitoring Points
- Modular Construction
- 5 MHz Output (Model M-3051)
- Option Available:
  10 MHz Output (Model M-3101)

Description

The Efratom M-3000 is the ultimate "state-of-the-art" rubidium oscillator, able to perform over a wide temperature range. It provides high stability even under severe vibration; warm-up time is less than 4 minutes at -55°C. The unit meets or exceeds the most severe military requirements.

The outstanding frequency stability of the Efratom M-3000 series rubidium oscillators allows for simplification of system design by extending the time between systems calibration/synchronization cycles. This rugged and compact unit is especially useful in airborne applications, as well as mobile ground operations.

The oscillator is available with a 5 MHz output (Model M-3051) or an optional 10 MHz output (Model M-3101). This unit has an aging rate of approximately 3.6E-10 the first year followed by 2E-10 per year thereafter. The short-term stability and phase noise specification are among the best available. The unit is specifically designed for low phase noise under vibration. Part of this is achieved by a low-g sensitive SC-cut quartz resonator in the crystal oscillator circuit and by controlling internal mechanical resonances.

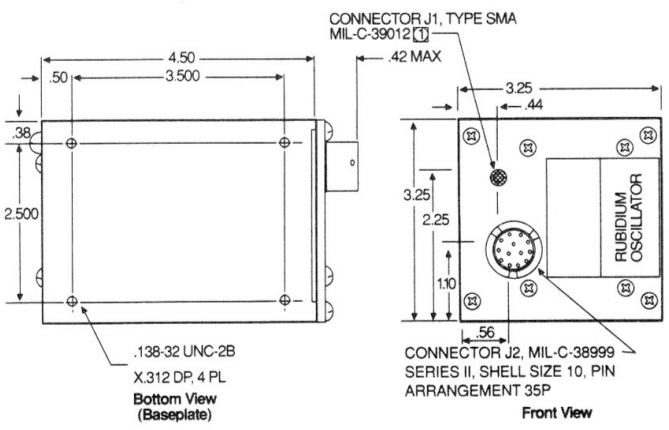
All components are QPL, or MIL-STD-883, Level B screened to the QPL levels. All parts are derated to assure reliable operation.

The M-3000 oscillator is 3.25 inches square by 4.50 inches long and weights approximately 4.0 pounds, making it one of the most compact rubidium oscillators available today. See figure at right for details and connector configuration.

Applications

In today's sophisticated electronic systems, atomic precision must often be maintained for both frequency and time. Below is a list of just a few of the applications for which the M-3000 is especially well suited:

- Mil-Satcom User Terminals
- Spread Spectrum Communication Systems
- Hi-AJ/Crypto Tactical Terminals
- Nodal-Switch Communications Terminals
- Time and Time Interval and Time Transfer Systems
- Missile Weapon Systems Guidance
- Prime Navigation Systems: Omega, VLF, Loran-C, and NAVSTAR-GPS User Equipment
- Relative Navigation and Positioning Systems for Tactical Theater
- Troposcatter Communication Terminals



M-3000 Series Military Rubidium Oscillator (continued)

FIGURE 1 – PHASE NOISE

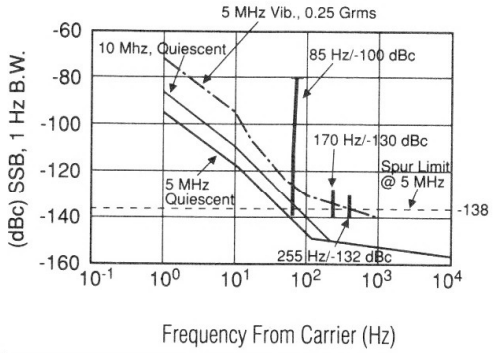
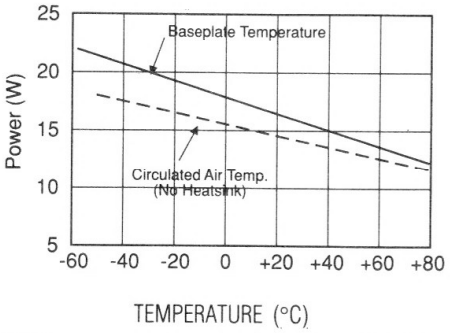


FIGURE 2 – INPUT POWER VS. TEMPERATURE (TYPICAL)



Electrical Performance

Unless otherwise stated, parameters are measured at +25°C ± 5°C; sea level ambient.

Output/Frequency/ Waveform	(1) / 5 MHz/Square (M-3051)
Output Option	(1) / 10 MHz/Sine (M-3101)
Output Level into 50 Ω Load	12.5 dBm (+1.5 /-3.0 dBm)(M-3051)
CMOS Compatible	7.0 dBm (±1.5 dBm)(M-3101)
Bite Output	Composite Lock (98%)
No-Fault/Fault Logic Level	0/1 (TTL Compatible)
Short-Term Stability	
1.0 Second (Allan Var.)	3E-11
10 Second (Allan Var.)	1E-11
100 Second (Allan Var.)	3E-12
Frequency Drift Per Month	6E-11 (After 14 days Ops)
1st / 2nd year and thereafter	3.6E-10 / 2E-10, per year
Freq. Accuracy At Shipment	±5E-11
Frequency Trim Range	3E-9
Setting Resolution	1E-11
Frequency Retrace	2E-11 (After 2 hr pwr on) @ 25°C & up to 48 hrs pwr off

Phase Noise (Figure 1) (dBc)	**10 MHz (M-3101)**	**5 MHz (M-3051)**
1 Hz from Carrier	-85	-90
100	-140	-143
300	-150	-150
10,000 (Noise Floor)	-155	-155

Harmonic Distortion	-30 dBc (Sine output only)
Non-Harmonic Distortion (Quiescent Operation)	10 Hz - 10 kHz (Figure 1) 10 kHz - 100 kHz, -138 dBc >100 kHz, -80 dBc
Input Voltage Range	23.4 to 28.6 Vdc (MIL-STD-704D)
Power, Steady State @ 25°C	18 W @ 26 Vdc (Figure 2)
@ -55°C	≤26 W
Power, warmup @ -55°C	<161 W Peak Max @ 28.6 V
Input Voltage Sensitivity	<1E-11 (for ±10% Vdc delta)
Warm-Up Time	
Time to Lock @ -55°	230 seconds
Minutes/Freq. @ -55°C	≤5 / 2E-9; ≤10 / 5E-10 (Consult factory for additional warm-up specs)

Environmental Performance

Operating Temp. Range	-55°C/+74°C baseplate
Freq. Offset Over Range	±5E-10
98°C Baseplate Emergency Temp. Offset	Parts in E+9 for 30 minutes
Storage Temp (Non-Ops)	–62°C to +95°C
Magnetic Field Sensitivity	3E-13/AM^{-1} (worst axis) (2.4E-11/gauss)
Pressure Sensitivity for	
Sea Level to 40,000 ft.	8E-11
Sea Level to 70,000 ft.	14E-11
Random Vibration (Non-Ops)	6 Grms 10-2000 Hz
Random Vibration (Ops)	Performance of Figure 1 for
Range/Levels	10-2000 Hz / 0.25 Grms (Consult factory for shock mounted profile and details)
Freq. Offset	≤5E-10 (average)
Shock - Level	30 G
Waveform/Duration	1/2 sine, 11 ms
Freq. Offset	<3E-8 momentary offset (worst orientation)
Radiation	(Consult factory for levels)
EMI	MIL-STD-461B (Class A1) (Consult factory for details.)
Relative Humidity	100% (MIL-E-5400) Water-sealed case
Reliability Spec.	MIL-HDBK-217D
MTBF, Ground Stationary	>81,000 hrs @ 50°C BP
Ground Mobile	>30,000 hrs @ 50°C BP
Airborne transport (Inhabited)	>25,000 hrs @ 74°C BP
Airborne fighter (Uninhabited)	>20,000 hrs @ 25°C BP
Parts	
IC Spec/Level	MIL-M-38510/B
or equiv. screen level	MIL-STD-883/B
Trans/Diodes/Level	MIL-S-19500/TX
or equiv. screen/level	MIL-S-750/TX
Passives	MIL, Established reliability

Physical

Weight/Volume	
Lbs./cubic inches	4.0 max / 47.5
kg/cubic cm	1.8 max / 779
Size (inches, nom. h/w/d)	3.25 / 3.25 / 4.5
(cm, h/w/d)	8.25 / 8.25 / 11.43
Warranty	1 year

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92718-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

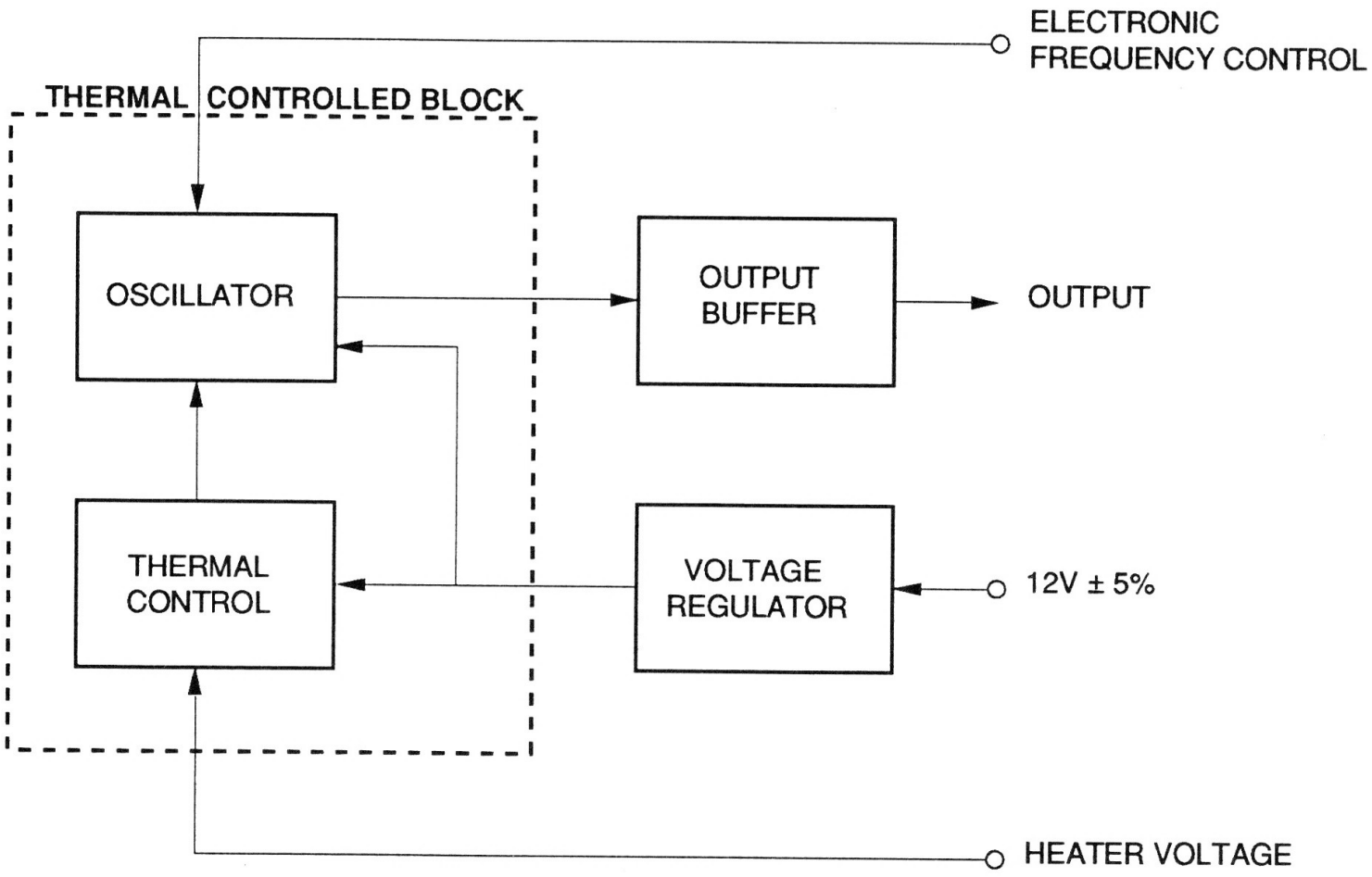
3/91

EMXO/ECXO Series Super-miniature Military and Commercial OCXO, SC-Cut Quartz Crystal Oscillators

This OCXO is specifically designed for user equipment and portable applications, where small size, low power consumption and fast warm-up are needed along with top OCXO stability performance.

MODEL EMXO/ECXO BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

EMXO Series Sub-Miniature Military Quartz Crystal Oscillator

- Std. Freq. 10.0 MHz, 10.23 MHz
- Designed for Low Power, Small Size Applications
- Fast Warm Up, ≤4 Min to 1E-8
- 1.3 Inches Cubed, ≤40 Grams
- Frequency Aging 5E-8/Year
- Temp Coefficient ±5E-9
- Options Available:

Output:	-S (sine)
	-T (TTL)
Temp. Range:	-A -55°C to +95°C
	-B -55°C to +71°C

Other Frequencies Specification Requirements – Contact Factory

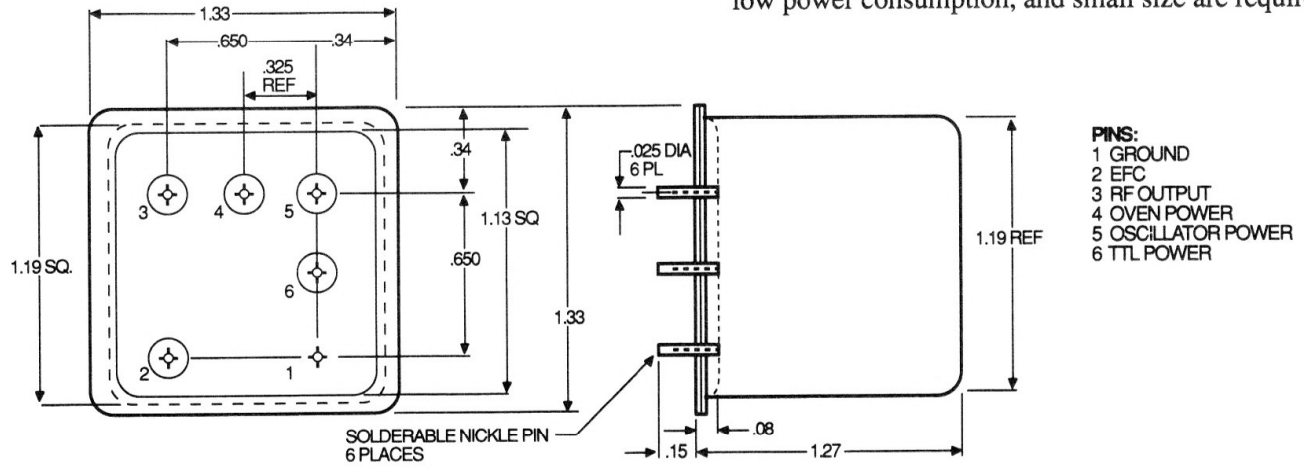
Description

The Model EMXO is an ultra-stable sub-miniature crystal oscillator designed for direct installation as a component in equipment and systems as well as for use as a laboratory frequency standard, local oscillator and time base. The 10 and 10.23 MHz sinusoidal or TTL output provides excellent short- and long-term stability over a wide range of environmental conditions.

The very small size and low power is achieved by the application of new resonator design concepts and technological breakthroughs which include new advances in package design. The EMXO closes the gap between today's most advanced large, high precision quartz crystal oscillators and the smaller, less expensive TCXO technology which does not have the needed performance for most applications.

Applications

High end crystal oscillator precision is required for both time and frequency in a wide variety of applications, including: radio navigation using Omega/VLF, Loran-C and satellite transmissions (GPS-TRANSIT-GOES); geophysical survey positioning systems; satellite tracking and guidance control; communications systems employing PCM and spread spectrum techniques; standard time and time interval generation and transfer. The EMXO is the most economical choice where a combination of excellent spectral purity, short-term and long-term stability is essential. It contributes to simplification of system design because of low frequency aging which extends the period of time needed between calibration or synchronization. This rugged, super-compact crystal oscillator is especially advantageous when utilized in mobile/transportable and portable applications where fast warm-up, low power consumption, and small size are required.



EMXO Series Sub-Miniature Military Quartz Crystal Oscillator (continued)

FIGURE 1 – PHASE NOISE

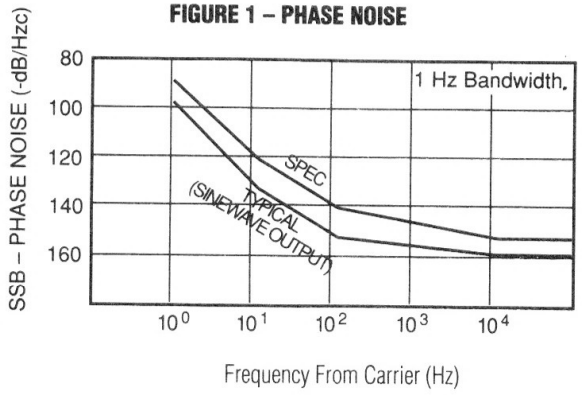
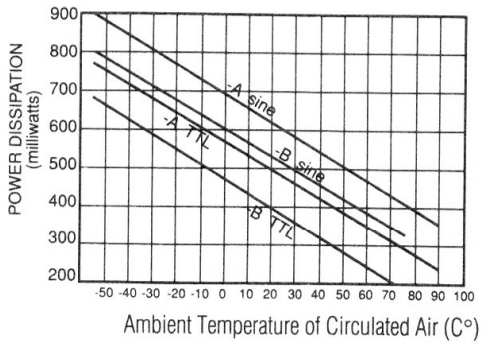


FIGURE 2 – POWER DISSIPATION



Electrical Performance

Output/Frequency/Waveform	(1) / 10 MHz/Sine (TTL Option)
Output Option	(1) / 10.23 MHz/Sine (TTL Option)
Output Level/Load	7.0 dBm, minimum/50 ohms
TTL Option:	10 LS TTL Loads
Duty Cycle	40 to 60%
Elec. Freq. Cont. Range (EFC)	±5E-7
EFC Input	0 to +5 Vdc, (+) Sensing
EFC Ext. Resistance	0 to 500 kohms
Short/Long-Term Stability	
0.1 Second (Allan Var.)	5E-12
1.0 Second (Allan Var.)	5E-12 (1E-11 for TTL)
10 Second (Allan Var.)	5E-12
Frequency Aging	Per Day ±5E-10 Per Year ±5E-8
Phase Noise $\mathcal{L}$ (-dBc/Hz)	(See Figure 1)
100	140 (130 TTL)
1000	150 (135 TTL)
10,000 (Noise Floor)	155 (140 TTL)
Harmonic Distortn (-dBc)	30 (N/A TTL)
Non-Harmonic Distortn (-dBc)	90 (80 TTL) (10 Hz to 100 MHz)
Frequency Retrace	± 1E-8 (After 1 hr. pwr. on @ 25°C & up to 24 hrs. power off.)
Input Voltage Range	**OSC:** +12 Vdc ±5% <30 MVP-P ripple, 1Hz/100kHz <100 MVP-P ripple, 100kHz/1MHz
	Oven: 10 to 15 Vdc, unregulated (Contact factory for higher than 15 Vdc requirements.)
	TTL: Additional +5 Vdc ±5%

Power, Steady State (mW)	**EMXO-A**	**EMXO-B**
See Fig. 2 @+25°C	600 (475 TTL)	500 (375 TTL)
@-55°C	900 (775 TTL)	800 (675 TTL)

Warm-Up Power @ 55°C	7 W
Input Voltage Sensitivity	1E-9 (For ±5% Vdc delta, on the osc. +12 Vdc input)
Load Change Sensitivity	±1E-9, for 10 pF Capacitance delta
Warm-up Time @ -55°C	≤2 minutes to 1E-7 ≤4 minutes to 1E-8

Environmental Performance

	EMXO-A	**EMXO-B**
Operating Temp. Range	-55°C to +95°C	-55°C to +71°C
Freq. Offset	±1E-8	±5E-9
	For other offsets, contact factory	
Storage Temp. (non-op)	-65°C to +125°C	
Temperature Shock	MIL-STD-202E, Method 107, Test Cond. A	
Altitude	To 80,000 ft	
Acceleration Sensitivity	≤1E-9 Per G (Gamma Vector)	
Vibration	MIL-STD-202E, Method 204 Test Cond. B	
Shock	MIL-STD-202E, Method 213 Test Cond. G	
Radiation	For hardness level, contact factory	
EMI/EMC Spec.	For performance levels, contact factory	
Relative Humidity	MIL-STD-202E, Method 106, Test Cond. D	
Reliability Spec	MIL-HDBK-217E	
Airborne Transport (MTBF)	Up to 330,000 hrs	
Design and Construction	Hermetically sealed	

Physical

Weight / Volume	
Lbs. / cubic inches	<0.09 / 2.2
kg / cubic cm	<.04 / 36
Size (inches, h / w / d)	1.27 / 1.33 / 1.33
(cm, h / w / d)	3.2 / 3.4 / 3.4
Warranty	1 year

Specify Model No.

EMXO -X -X Frequency (in MHz)

-X: -A -55°c to +95°C, or -B -55°C to +71°C

Output: -S sine, or -T TTL

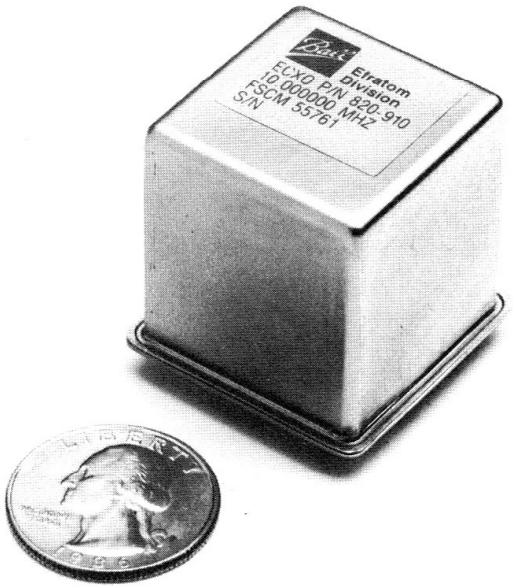
Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

3/91

Ball Efratom Division

ECXO Series Sub-Miniature Commercial Quartz Crystal Oscillator



- Standard Freq. 10.0 MHz, 10.23 MHz
- Designed for Low Power, Small Size Applications
- Fast Warm Up, ≤4 Min to 1E-8
- 1.3 Inches Cubed, ≤40 grams
- Frequency Aging 5E-8/Year
- Temp. Coefficient ±5E-9
- Options Available:

  Outputs: -S (sine)
  -T (TTL)

  Other Frequencies

Description

The Model ECXO is an ultra-stable sub-miniature crystal oscillator designed for direct installation as a component in instruments and systems as well as for use as a laboratory frequency standard, local oscillator and time base. The 10 and 10.23 MHz sinusoidal or TTL output provides excellent short- and long-term stability over a wide range of environmental conditions.

The very small size and low power is achieved by the application of new resonator design concepts and technological breakthroughs which include new advances in package design. The ECXO closes the gap between today's most advanced large, high-precision quartz crystal oscillators and the smaller, less expensive TCXO technology which does not have the needed performance for most applications.

Applications

High-end crystal oscillator precision is required for both time and frequency in a wide variety of applications, including a variety of precision instruments such as synthesizers, counters and spectrum analyzers as well as radio navigation using Omega/VLF, Loran-C, satellite transmissions (GPS-TRANSIT-GOES); geophysical-survey positioning systems; standard time and time-interval generation and transfer. The ECXO is the most economical choice where a combination of excellent spectral purity, short-term and long-term stability are essential. It contributes to simplification of system design because of low frequency aging which extends the period of time needed between calibration or synchronization. This rugged, super-compact crystal oscillator is especially advantageous when utilized in mobile/transportable and portable applications where fast warm-up, low power consumption and small size are required.

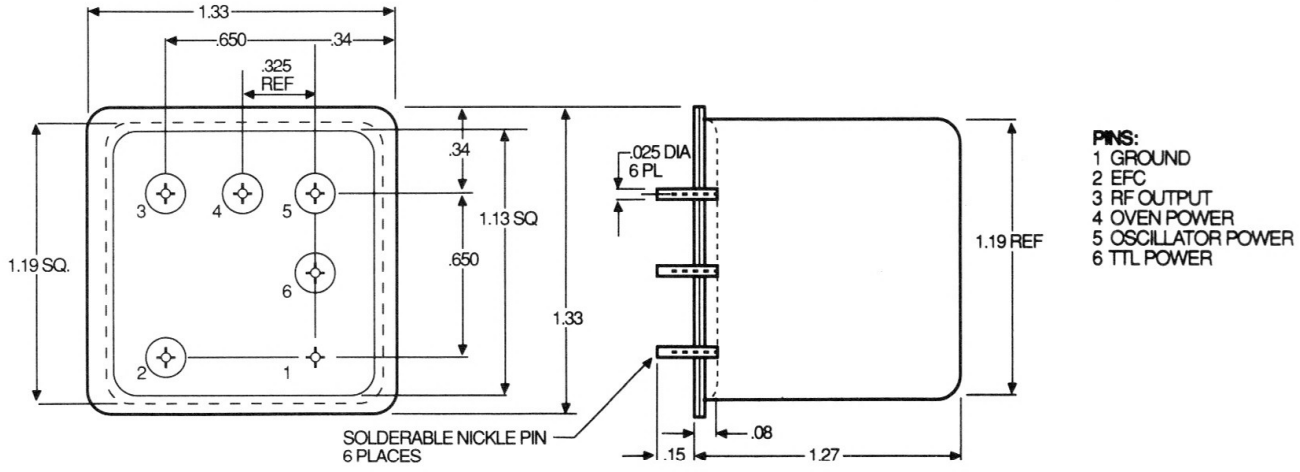


FIGURE 1 – PHASE NOISE

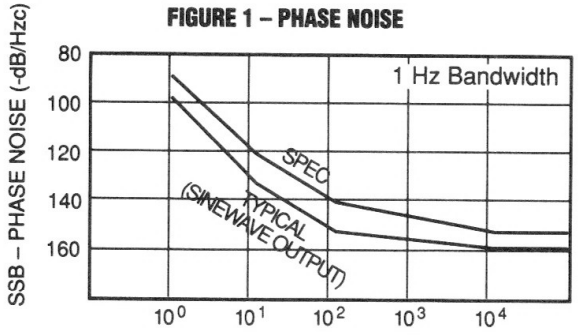
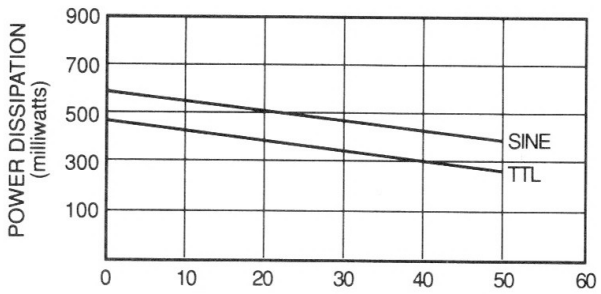


FIGURE 2 – POWER DISSIPATION



Electrical Performance

Output/Freq./Waveform	(1) / 10 MHz/Sine (TTL Option)
Output Option	(1) / 10.23 MHz/Sine (TTL Option)
Output Level/Load	7.0 dBm, minimum/50 ohms
TTL Option:	10 LS TTL Loads
Duty Cycle	40 to 60%
Elec. Freq. Cont. Range (EFC)	± 5E-7
EFC Input	0 to +5 Vdc, (+) Sensing
EFC Ext. Resistance	0 to 500 kohms
Short/Long-Term Stability	
0.1 Second (Allan Var.)	5E-12
1.0 Second (Allan Var.)	5E-12 (1E-11 for TTL)
10 Second (Allan Var.)	5E-12
Frequency Aging	Per Day ± 5E-10
	Per Year ± 5E-8
Phase Noise $\mathcal{L}$ (-dBc/Hz)	(See Figure 1)
100	140 (130 TTL)
1000	150 (135 TTL)
10,000 (Noise Floor)	155 (140 TTL)
Harmonic Distortn (dBC)	30 (N/A TTL)
Non-Harmonic Distortn (-dBC)	90 (80 TTL) (10 Hz to 100 MHz)
Frequency Retrace	± 1E-8 (After 1 hr pwr on @ 25°C & up to 24 hrs. power off)

Input Voltage Range	**Osc:** +12 Vdc ± 5% <30 mVp-p ripple, 1 Hz/100 kHz <100 mVp-p ripple, 100 kHz/1 MHz **Oven:** 10 to 28 Vdc, unregulated TTL: Additional +5 Vdc ± 5%		
Power, Steady State (mW)		**Sine**	**TTL**
See Fig. 2	0°C	600	475
	25°C	500	375
	50°C	400	275
Warm-Up Power	7 W		
Input Voltage Sensitivity	1E-9 (For ±5% Vdc delta, on the osc. +12 Vdc input)		
Load Change Sensitivity	±1E-9, for 10 pF capacitance delta		
Warm-up Time	≤2 minutes to 1E-7 ≤4 minutes to 1E-8		

Environmental Performance

Operating Temp. Range	0°C to +50°C (Note 1)
Freq. Offset Over Range	± 5E-9
Storage Temp. (non-ops)	-65°C to +100°C

Physical

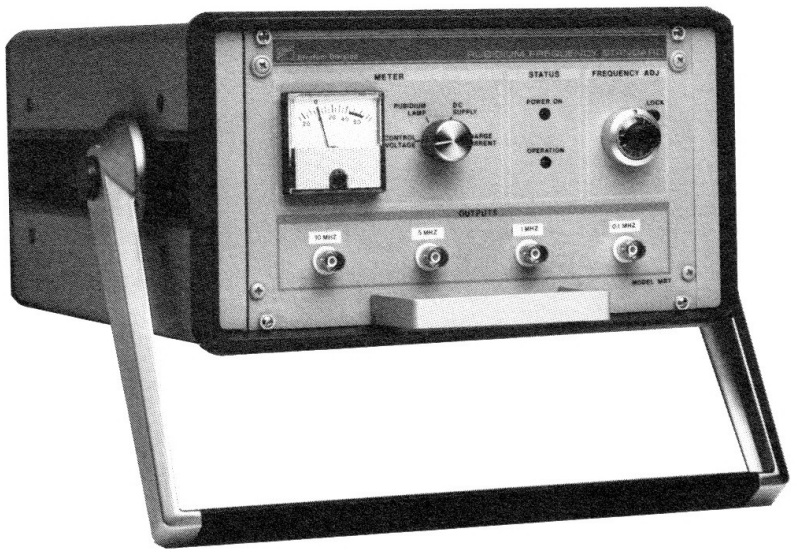
Weight / Volume	
Lbs. / cubic inches	<0.09 / 2.2
kg / cubic cm	<.04 / 36
Size (inches, h / w / d)	1.27 / 1.33 / 1.33
(cm, h / w / d)	3.2 / 3.4 / 3.4
Warranty	1 year

Note 1: Contact factory for extended operating range.

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

3/91



MRT series, (½) 19 inch rack Rubidium Frequency Standard

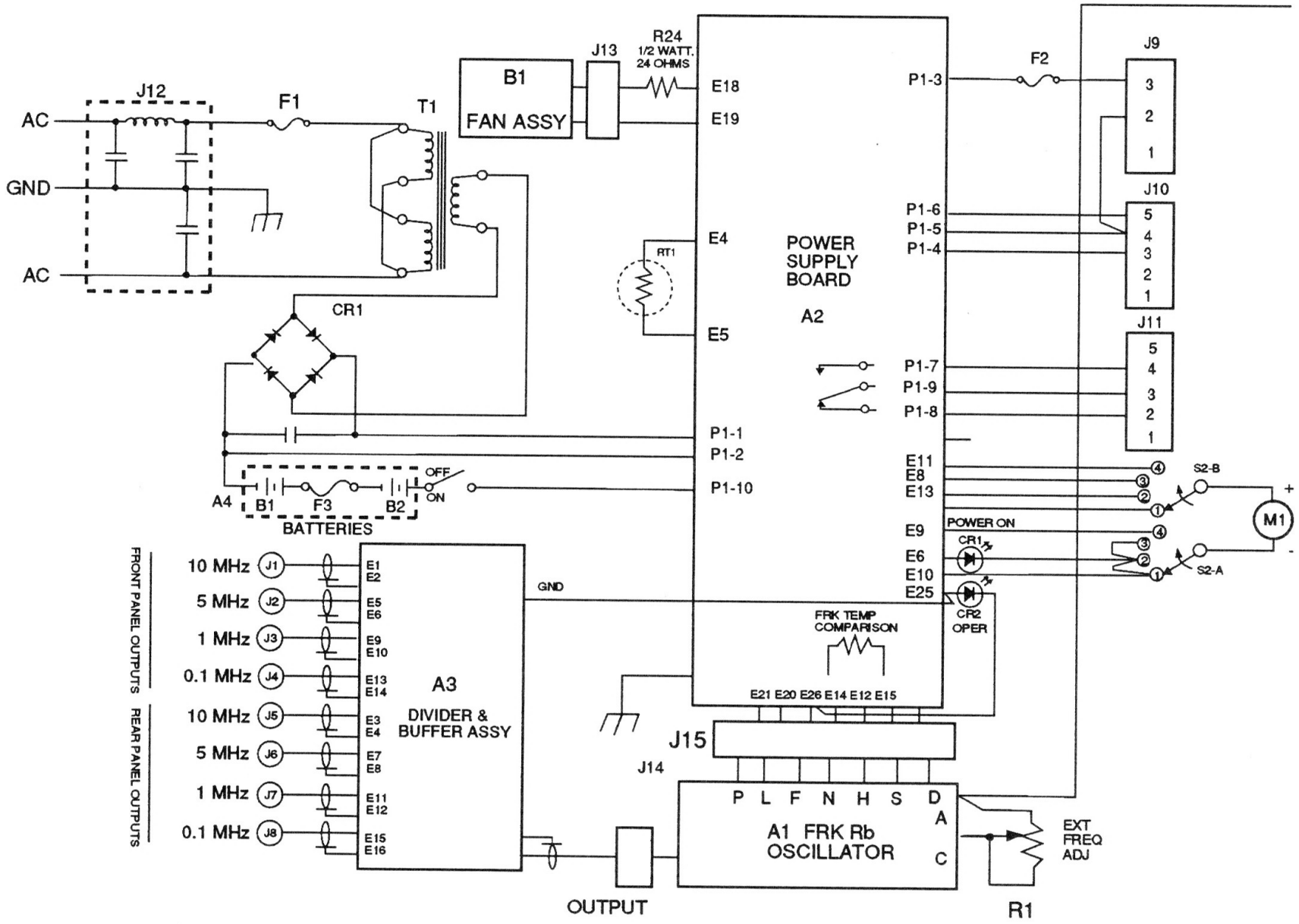
This unit represents Model FRK rubidium technology in a portable or rack mounted configuration. The MRT is designed for ac/dc operation and has a 5-hour internal back-up battery.

The MRT is generally used in ground stations, laboratories, bench test stations, check-out equipment and in facilities as a house reference.

The MRT-HT version provides additional temperature stability through full 19 inch rack mounting and an added fan assembly. Due to the additional thermal structure, the internal battery operation is about 3.5 hours, instead of 5 hours.

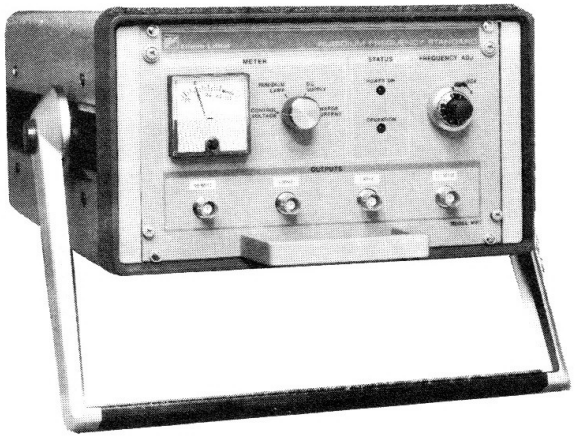
MODEL MRT BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

MRT Rubidium Frequency Standard



- Excellent for Lab, Ground Station and Test Equipment Applications
- Outstanding Stability
- High Spectral Purity
- Front and Rear Outputs
- Internal Battery – Portable
- Options Available:
  – H (Low Aging)
  – LN (Low Noise)
  1 PPS Outputs

Description

The Model MRT Rubidium Frequency Standard is part of Efratom's family of Frequency Standards/Test Instruments. The MRT employs a rugged, compact design consisting of the Model FRK-L/H rubidium oscillator, dividers, buffer amplifiers and a regulated power supply including stand-by batteries. The MRT is available for rack mount installation, occupying half the width of a standard 19" rack, with 5.25 in. panel height, or with a portable instrument case for laboratory or field use. Buffered outputs of 10, 5, 1, and 0.1 MHz sine waves are provided at the front and rear panel connectors. All outputs feature short circuit protection. Different output combinations are optionally available and the factory should be contacted for specific requirements. A front panel helipot permits fine frequency adjustments to ±2E–12 within the specified trim range. A front panel meter allows monitoring of rubidium lamp voltage, crystal control voltage, DC supply and battery pack charging current. Each function is independently selectable by means of a front panel mounted switch.

In addition to the four buffered outputs available on the rear panel of the Model MRT, other features included are two separate fuses for input power, a switch to enable/disable the internal battery supply, receptacles for external DC power, 110/220 Vac line voltage, remote monitoring of oscillator lock condition and provision for connecting auxiliary equipment to provide remote frequency control.

Applications

The Model MRT may be used as a master oscillator in laboratories, on aircraft, aboard ships and for field calibration services. It provides ultra-stable frequency and time intervals with excellent short-term stability and phase noise characteristics as normally required for narrow band communication; radio astronomy; doppler radar; satellite tracking and guidance control; Very Long Baseline Interferometry. Other uses are VLF and satellite navigation; television frequency control; precise timekeeping systems; time and frequency transport.

Operation

The basic Model FRK makes use of the atomic resonance of rubidium (^{87}Rb) to control the frequency of a quartz crystal oscillator. A microwave signal derived from the crystal oscillator is applied to the ^{87}Rb vapor within a cell. The light of a rubidium spectral lamp also passes through this cell and illuminates a photo detector. When the frequency of the applied rf signal corresponds to the frequency of the ultra-stable rubidium atomic resonance, the light is absorbed to an increased extent causing a change in the photo detector current. This effect is used to generate a control signal which permits continuous automatic regulation of the quartz crystal oscillator frequency of 10 MHz. This is fed through dividers and buffer amplifiers and provides standard frequency outputs of 10, 5, 1 and 0.1 MHz.

MRT Rubidium Frequency Standard (continued)

FIGURE 1. TIME DOMAIN STABILITY

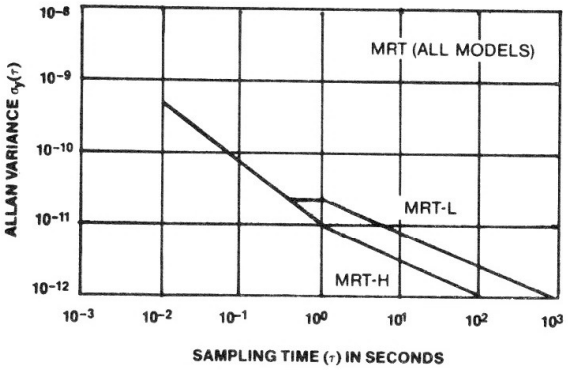
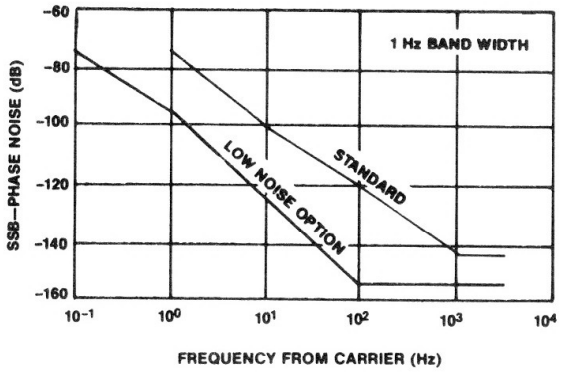
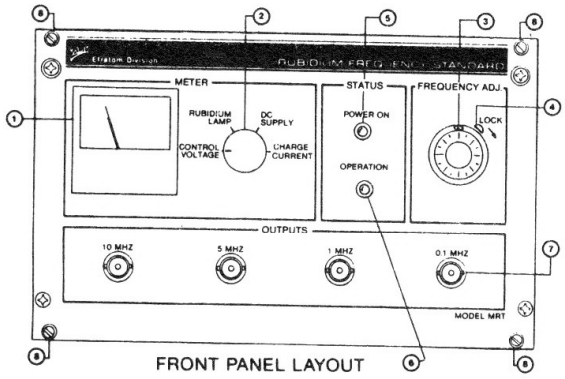


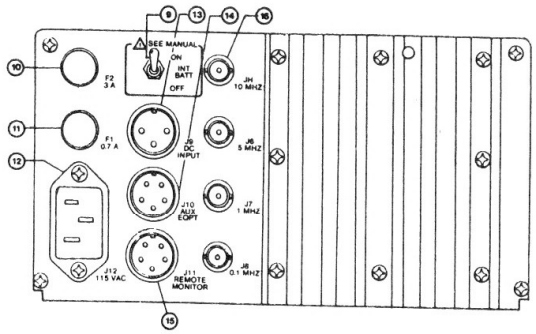
FIGURE 2. PHASE NOISE





FRONT PANEL LAYOUT

1 METER
2 METER FUNCTION SWITCH (S2)
3 FREQUENCY ADJUST VERNIER (R4)
4 FREQUENCY ADJUST LOCK
5 POWER INDICATOR
6 OPERATION INDICATOR
7 OUTPUTS J1, J2, J3, J4
8 RACK MOUNTING SCREW
9 INT BATTERY SWITCH



REAR PANEL LAYOUT

10 F2 3A
11 F1 0.7A
12 AC POWER INPUT RECEPTACLE J12
13 DC INPUT RECEPTACLE J9
14 AUX EQUIPMENT J 10
15 REMOTE MONITOR J11
16 OUTPUTS J5, J6 J7, J8

Electrical Performance

Outputs	10 MHz, 5 MHz, 1 MHz 0.1 MHz both front and rear; 1 Vrms into 50 ohms, sinewave.
Option	1 PPS instead of one 0.1 MHz output (Consult factory for optional outputs)
Phase Noise (SSB 1 Hz BW)	>120 dB @ 100 Hz from carrier >145 dB @ 1000 Hz from carrier
Low Noise Option-LN	> 125 dB @ 10 Hz from carrier >155 dB @ 100 Hz from carrier
Aging	-L 4E-11/month -H 1E-11/month
Short-Term Stability	-L 3E-11, τ = 1 sec 1E-11, τ = 10 sec 3E-12, τ = 100 sec
	-H 1E-11, τ = 1 sec 3.16E-12, τ = 10 sec 1E-12, τ = 100 sec
Trim Range	2E-9
Fine Tuning Resolution	2E-12
Voltage Variation	<1E-11/± 10% Vac
Warm-Up Characteristics	<10 minutes to reach 2E-10 at 25°C ambient
Input Power	50 W at 115/220 Vac (+10%, -15%), 47-400 Hz <30 W at 23-32 Vdc
Internal Battery	More than 5 hours capacity at 25°C ambient. Automatic recharge.

Environmental Performance

Operating Temp. Range	-L <4E-10 from -10°C to +50°C -H 1E-10 from -10°C to +50°C
Storage Temp	-40°C to +60°C
Altitude	1E-13/mbar (sea level to 40,000 ft.)
Humidity	95%
Magnetic Field	≤4E-13/Am^{-1} (3E-11/gauss)

Physical

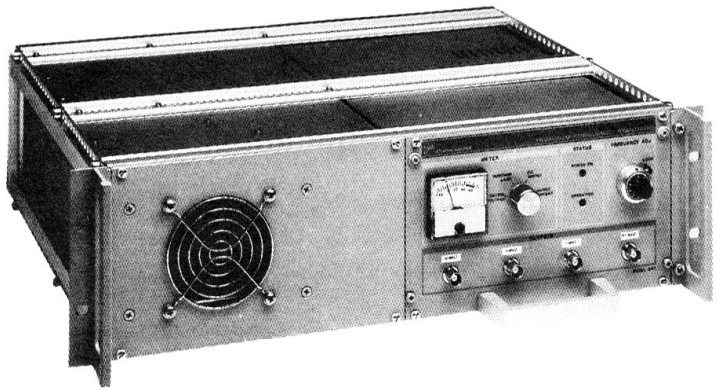
Size	Panel height 5.05 in. high x 8.38 in. wide x 14.50 in. long. Suitable for 19" rack, or portable carrying case.
Weight	35 lbs. with battery and portable case, 28 lbs. without portable case.
Controls/Indicators	Power and operation: LED indicators for power and operation: meter to monitor VCXO control voltage, Rb lamp, dc supply voltage battery charging current: battery switch: frequency vernier potentiometer.
Connectors	Frequency outputs, ext. battery, aux. equipment, remote monitor.
Warranty	1 year
Option	5 year extended warranty

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92718-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

Efratom Division

MRT-HT Rubidium Frequency Standard



- Part No. 808-100-18
- Specially Designed for 19" Rack Mounting
- Excellent for Lab, Ground Station and Test Equipment Applications
- Outstanding Stability
- High Spectral Purity
- Front and Rear Outputs
- Internal Battery – Back-up
- Options Available:
  5 Year Warranty

Description

The Model MRT-HT Rubidium Frequency Standard is part of Efratom's family of Modular Frequency Standards/Test Instruments. The MRT-HT employs a rugged 19" rack compatible design consisting of the Model FRK-H rubidium oscillator, dividers, buffer amplifiers, a regulated power supply, and a special thermal structure with a fan. This extends the MRT-HT to a full 19" rack compared to its MRT counterpart which occupies only one-half of a 19" rack. Buffered outputs of 10, 5, 1, and 0.1 MHz sine waves are provided at the front and rear panel connectors. All outputs feature short-circuit protection. A front panel helipot permits fine-frequency adjustments to ±2E-12 within the specified trim range. A front panel meter allows monitoring of rubidium lamp voltage, crystal control voltage, dc supply and battery pack charging current. Each function is independently selectable by means of a front panel mounted switch.

In addition to the four buffered outputs available on the rear panel of the Model MRT-HT, other features included are two separate fuses for input power, a switch to enable/disable the internal battery supply, receptacles for external dc power, 110/220 Vac line voltage, remote monitoring of oscillator lock condition and provision for connecting auxiliary equipment to provide remote frequency control.

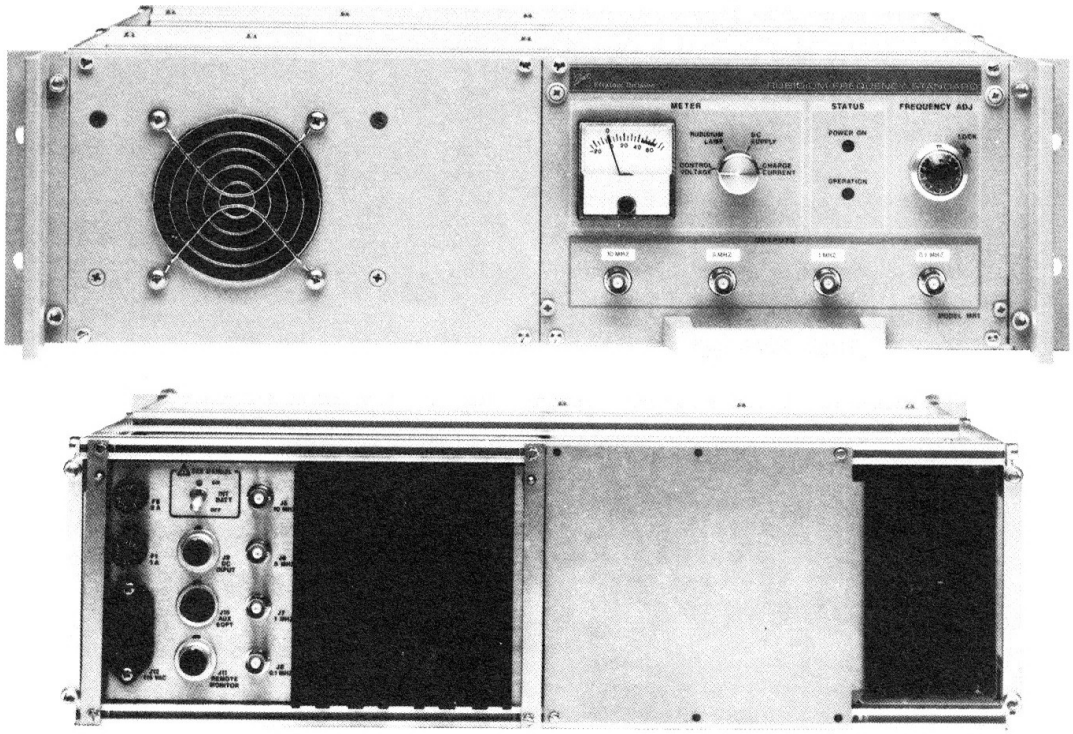
Overall dimensions of the Model MRT-HT are 5.25 in. x 19 in. x 14.50 in. and the total weight including battery pack is 40 lbs.

Applications

The Model MRT-HT may be used as a master oscillator in laboratories, on aircraft, aboard ships and for field calibration services. It provides ultra-stable frequency and time intervals with excellent short-term stability and phase noise characteristics as normally required for narrow band communication; radio astronomy; doppler radar; satellite tracking/guidance control; Very Long Baseline Interferometry. Other uses are VLF and satellite navigation; television/networks frequency control; precise timekeeping systems; time and frequency transport.

Operation

The basic Model FRK makes use of the atomic resonance of rubidium (^{87}Rb) to control the frequency of a quartz crystal oscillator. A microwave signal derived from the crystal oscillator is applied to the ^{87}Rb vapor within a cell. The light of a rubidium spectral lamp also passes through this cell and illuminates a photo detector. When the frequency of the applied rf signal corresponds to the frequency of the ultra-stable rubidium atomic resonance, the light is absorbed to an increased extent causing a change in the photo detector current. This effect is used to generate a control signal which permits continuous automatic regulation of the quartz crystal oscillator frequency of 10 MHz. This is fed through dividers and buffer amplifiers and provides standard frequency outputs of 10, 5, 1 and 0.1 MHz.



Electrical Performance

Outputs	10 MHz, 5 MHz, 1 MHz, 0.1 MHz both front and rear; 1 Vrms into 50 ohms, sinewave.
Phase Noise (SSB 1 Hz BW)	>120 dBc @ 100 Hz from carrier >145 dBc @ 1000 Hz from carrier
Frequency Drift	1E-11/month
Short-Term Stability	1E-11, τ = 1 sec 3.16E-12, τ = 10 sec 1E-12, τ = 100 sec
Trim Range	2E-9
Fine Tuning Resolution	±2E-12
Voltage Variation	<1E-11/±10% Vac
Warm-Up Characteristics	<10 minutes to reach 2E-10 at 25°C ambient
Input Power	50 W at 115/220 Vac(+10%, -15%), 47-400 Hz <30 W at 23-32 Vdc
Internal Battery	More than 3.5 hours capacity at 25°C ambient. Automatic recharge.

Environmental Performance

Operating Temperature	-10°C to +50°C
Temperature Coefficient	1E-10
Storage Temperature	-40°C to +60°C
Altitude	1E-13/mbar (sea level to 40,000 ft)
Humidity	95%
Magnetic Field	<4E-13/Am^{-1} (3E-11/gauss)

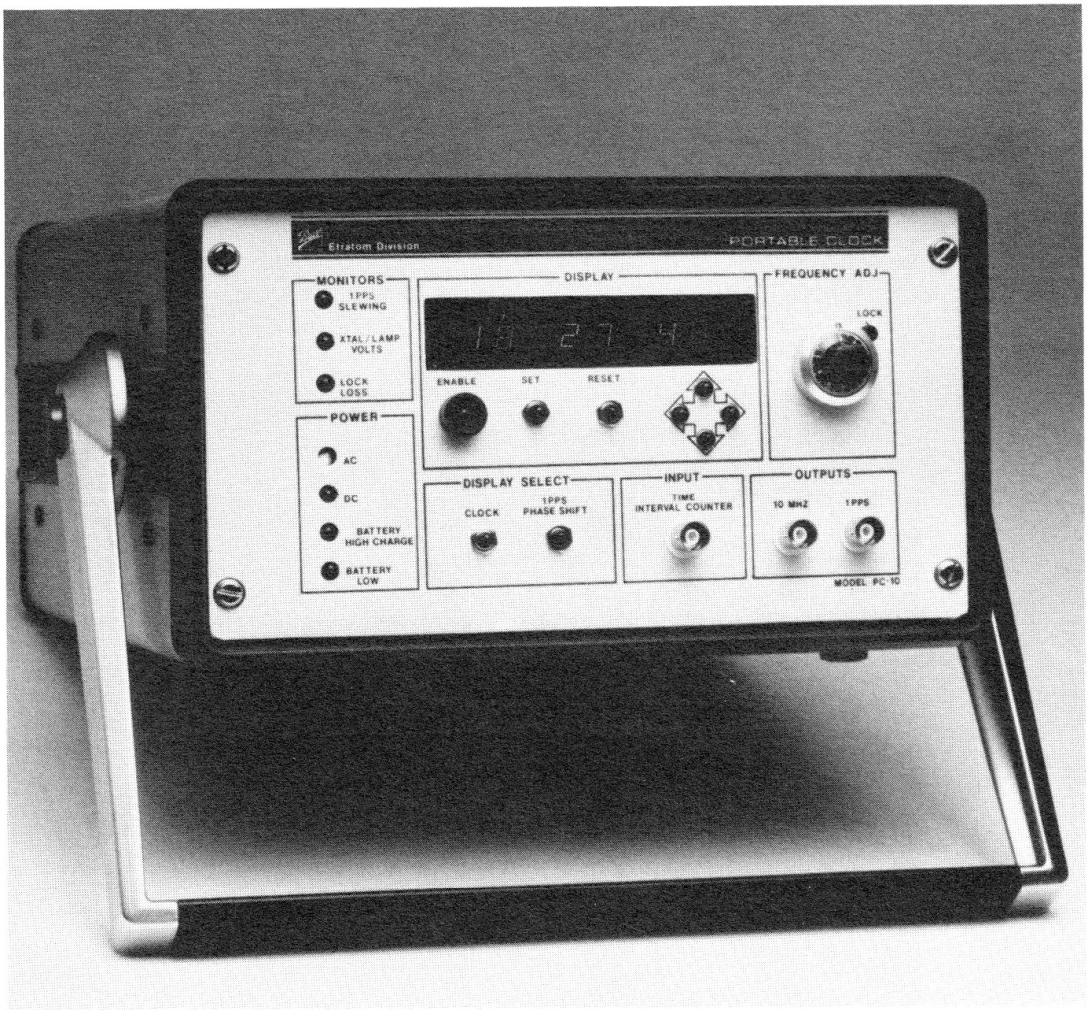
Physical

Size	Panel height 5.25 in. high x 19 in. wide x 14.50 in. long. 19" rack mountable P/N M19
Weight	40 lbs. with batteries
Controls/Indicators	Power and operation: LED indicators for power and operation: meter to monitor VCXO control voltage, Rb-lamp, d.c. supply voltage battery charging current: battery switch: frequency vernier potentiometer.
Connectors	Frequency outputs, ext. battery, aux. equipment, remote monitor.
Warranty	1 year
Option	5 year extended warranty

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

3/91

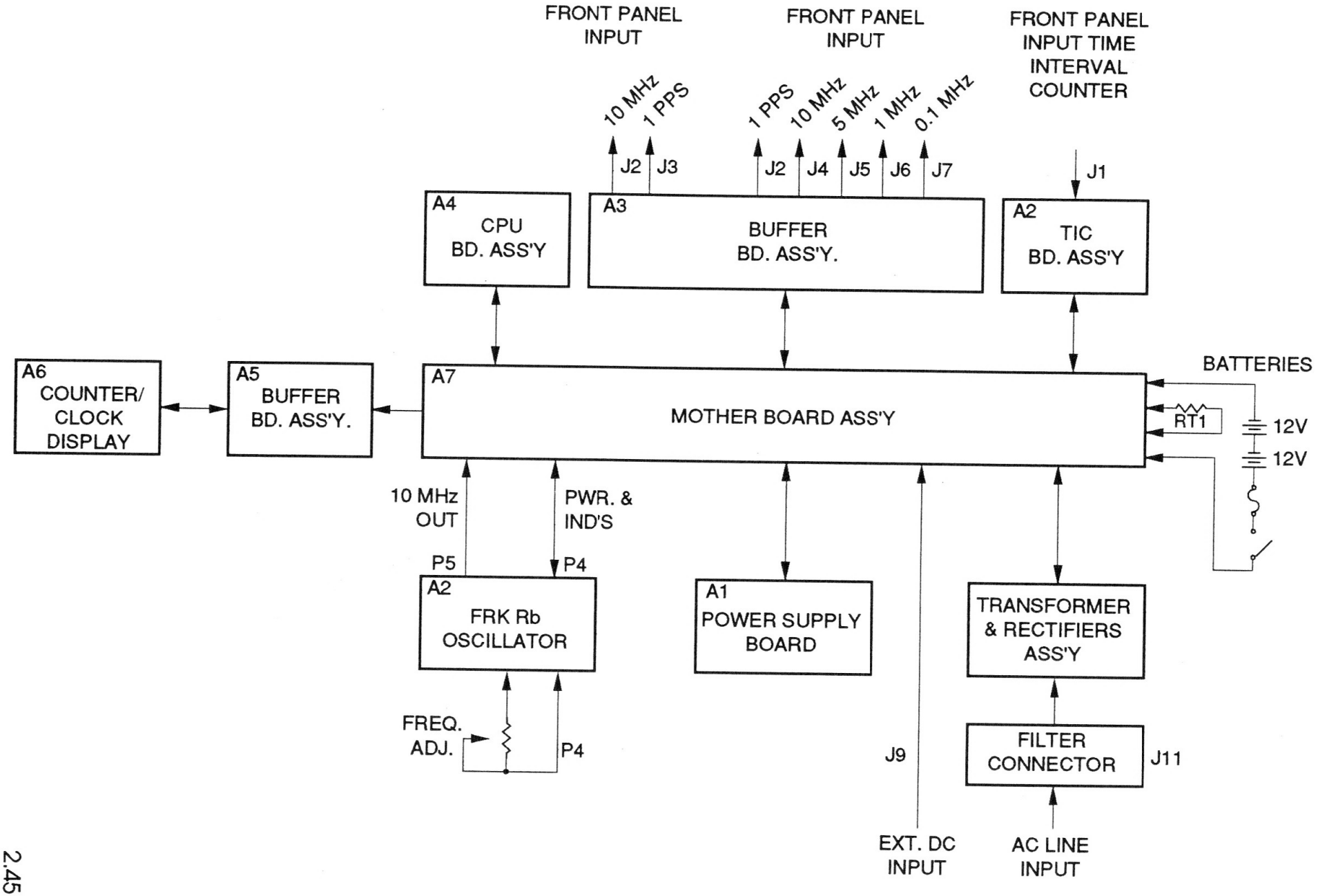


PC-10 Rubidium Portable Clock

This unit is a special (½) 19" rack portable frequency standard, designed for time transfer. It provides 6 hours of battery life and represents the smallest, lowest weight atomic time transfer clock available. It can be set as the master via a phase-shiftable 1 pps. An interval counter and display are included to indicate the time delta between master and slave.

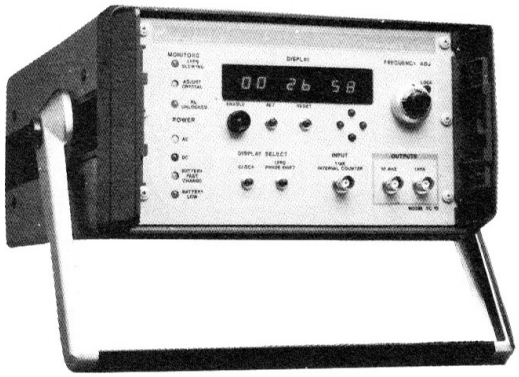
MODEL PC-10 BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

PC-10 Atomic Portable Clock



- Microprocessor Controlled
- 10, 5, 1, 0.1 MHz Sine & Precision 1-PPS (CMOS/TTL Compatible)
- Internal Time Interval Counter
- Rubidium Stability
- Ac, Dc & Internal Battery Operation
- Small & Lightweight

Description

The Model PC-10 Atomic Portable Clock/Frequency Standard is a self-contained multi-purpose instrument which is designed for both laboratory and portable field operation. The PC-10 provides precise time of day (TOD) information, a precision 1-PPS CMOS/TTL compatible signal and 10, 5, 1 and 0.1 MHz sinusoidal output at 1 vrms into a 50 ohm load. The basic reference frequency and all timing functions are derived from a highly stable internal rubidium oscillator, Efratom Model FRK-H. The time interval measurements and synchronization capabilities are controlled by an on-board central processing unit (CPU). Sync capability and time difference measurements between the internal 1-PPS to an external 1 PPS signal are provided. Sync can be accomplished either automatically or manually with accuracy to within 100 nsec. Time interval measurements can be made to ±20 nsec accuracy. The unit can be operated from either an ac or dc power source, including field operation of up to 6 hours on internal batteries. Battery recharging is automatic while the unit is operating on ac power. To conserve battery life, the clock display is blanked during portable operation, but may be activated momentarily by engaging the "CLOCK" push button.

Applications

The Model PC-10 is used to transfer precise time from one location to another via ground, air or sea, and for field calibration services. It provides ultra stable frequencies along with precise time accuracy as it applies to "flying clocks," geophysical survey positioning systems, emitter locator, bistatic radar and precise time keeping systems. Depending on conditions, time accuracy of 200 to 300 nsec should be easily achieved during a 6 hour portable operation.

Due to its small rubidium oscillator, the PC-10 is relatively small and lightweight when compared to other atomic-based alternatives.

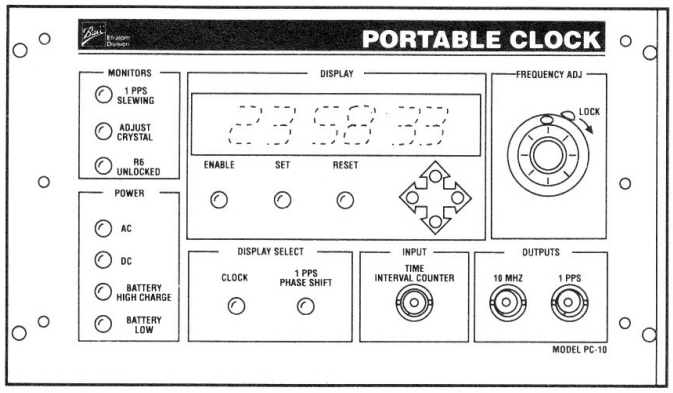
Operation

Time Interval Counter (TIC): When an external 1-PPS CMOS/TTL compatible signal is applied to the Time Interval Counter input connector, the TIC will measure the time interval between the internally generated 1-PPS and the external signal. The first displayed results will indicate the time difference between the two signals, within ±100 nsec. The CPU will then bracket the external 1-PPS using a 12.5 nsec per step delay line to determine the residual time difference. The number of delay line steps is used to calculate the 10 nsec digit, which then indicates the time difference between the last calibration to a reference clock, and the external pulse to within ±20 nsec. (This digit is updated every second.)

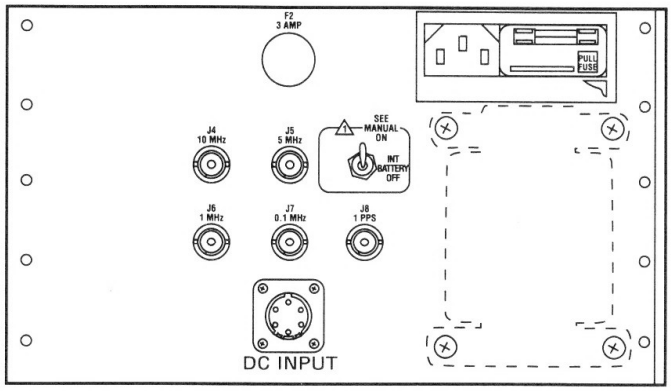
Automatic Synchronization: To automatically synchronize the internal pulse to the external pulse (to within 100 nsec), the user need only connect a 1-PPS source to the Time Interval Counter input connector and to press the "ENABLE" and "SET" buttons on the front panel. The residual time difference (<100 nsec) is stored by the CPU and subtracted from all future time difference measurements until the PC-10 Synchronization is reset.

Manual Synchronization: An internal phase shifting network in conjunction with front panel controls allows the phase of the internal 1-PPS signal to be shifted manually. This allows manual synchronization of the internal pulse to the external pulse (to within 100 nsec). Each button depression will advance or retard the internal 1 pulse phase from 100 nsec to 0.1 seconds, depending on which digit is selected. If the button is held down for longer than 1 second, the 1-PPS phase will change at a 4-digit per second rate. The phase may be advanced or retarded 1+ seconds, with the resulting carry or borrow being reflected in the TOD clock. The phase may be brought back to the original value by pressing the "RESET" button or may be used as the Synchronization by pressing the "ENABLE" and "SET" push buttons.

PC-10 Atomic Portable Clock (continued)



Front Panel View



Rear Panel View

Electrical Performance

Outputs	10, 5, 1, 0.1 MHz sinusoidal @ 1 Vrms into 50 ohm from the rear panel. 10 MHz sinusoidal @ 1 Vrm into 50 ohm and 1 PPS CMOS/TTL compatible signal from the front and rear panel
1 PPS Characteristics	
Amplitude	5 volts ±10% peak into 50 ohm load
Width	10µs ±2µs
Rise Time	<10 nsec
Fall Time	<100 nsec
Jitter	<10 nsec
Synchronization	
Automatic	Syncs internal 1-PPS to leading edge of (TTL compatible) external reference pulse to within 100 nsec
1 PPS Phase Shifting	
Manual	Allows the phase of the internal 1-PPS to be advanced/retarded manually in the following steps: 100,000 µsec/step 10,000 µsec/step 1,000 µsec/step 100 µsec/step 10 µsec/step 1 µsec/step 0.1 µsec/step
Time Interval Counter	Measures time interval between internal 1-PPS signal and external TTL compatible 1-PPS, to within ±20 nsec accuracy
Power Requirements	50 W at 115/220 Vac (+10%, -15%) 50-400 Hz <30 W at +22 to +32 Vdc
Internal Battery	6 hours (@ 25°C ambient) at rated battery capacity if display remains off.
Internal Frequency Standard Characteristics	
Aging	≤1E-11/month
Short-Term Stability	≤1.0E-11 τ = 1 sec ≤3.2E-12 τ = 10 sec ≤1.0E-12 τ = 100 sec
Setting Resolution	2E-12
Frequency Trim Range	2E-9

Environmental Performance

Operating Temperature	<1E-10 from -10°C to +45°C*
Storage Temperature	-40°C to +60°C (upper limit of battery)
Altitude	5E-11 S.L. to 40,000 ft. (<1E-13/mbar) (not limited to 40,000 ft.)
Magnetic Field	5E-12 gauss
Warm-up	2E-10 in 10 minutes at 25°C
Vibration (with lso's)	MIL-STD-167-1
Shock	MIL-E-5400, Class 1 (30G)
EMC	MIL-STD-461 Notice 3, Class A

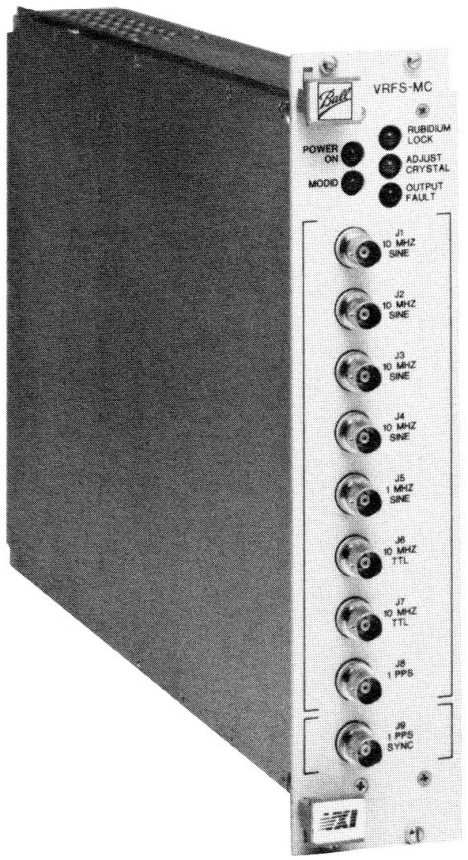
Physical

Size	Approximately 6.0" high x 10.0" wide x 15.0" long with instrument case (not including carrying handles)
Weight	Approximately 35 lbs. with battery and portable case included
Connectors	All input and output signals are to BNC female type connectors Dc input/output is from a MIL-C-26482 series 1 type connector Ac input is to a filtered, 3-prong male connector (Ac cord supplied)
Indicators	AC operation DC operation Adjust Crystal Rb Unlocked 1 PPS Slewing Battery High Charge Low Battery
Controls	Push button for setting clock and phase shifter, frequency vernier locking potentiometer, battery switch
Display	10 digit, seven-segment, red LED display
Provides	TOD information, time interval information and phase shifting information
Warranty:	1 year

*While in High Charge mode, max. ambient temp. +40°C

Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92716-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/90 40; Telex 529701; Fax 08104/99 18
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

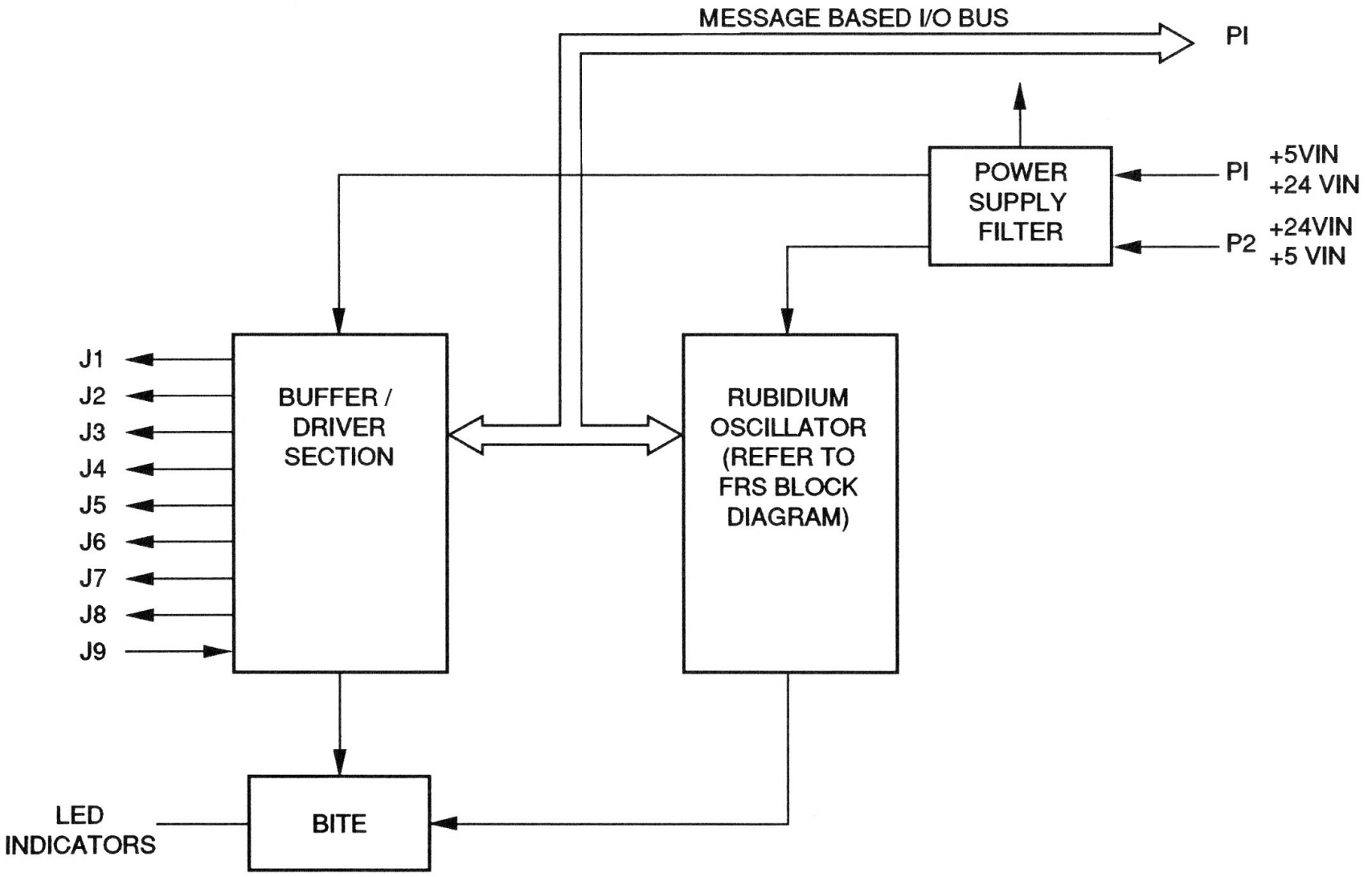


VRFS-MC: VXIbus Rubidium Frequency Standard

This module is an ultra-stable miniature atomic oscillator suitable for use as a VXIbus system clock designed to be installed in a C-size mainframe configured in accordance with the VXIbus Specification. This module is a message-based device that offers timing accuracy of ± 1 ppb over its specified operating temperature at the VXIbus system clock frequency of 10 MHz and provides up to eight outputs which can be 1 PPS, 1 MHz sine, 10 MHz sine, and 10 MHz TTL. The module also allows one 1 PPS input from an external source.

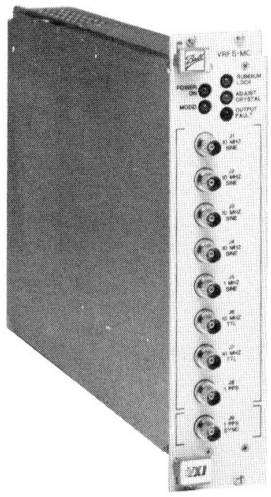
MODEL VRFS-MC BLOCK DIAGRAM

Ball Efratom Division



Ball Efratom Division

VRFS-MC: VXIbus Rubidium Frequency Standard



- Message Based Servant Device
- Two-slot wide, C-size VXIbus Module
- Sine and/or TTL Outputs
- Available in 1 Hz*, and 0.1, 1, 5, and 10 MHz Outputs
- Supports EG, I, and I4 Protocols
- Provides Atomic Frequency Standard Output Stability
- Provides both Status and ID Registers (with optional 1 PPS output)*

Description

The Model VRFS-MC is an ultra-stable miniature atomic oscillator to be supported by a C-size mainframe and resource manager configured in accordance with (IAW) the VXIbus Specification.

Applications

The VRFS-MC is a message based device that provides multiple outputs. One output can be used as a VXIbus system clock, by means of a front-panel-to-front-panel connection from the VRFS-MC to the resource manager. Other outputs are available as stable sources for calibration or test applications.

Physical

Weight	8.0 lbs.
Size	Two-slot Wide, C-Size Module IAW VXIbus Specifications
Connectors	P1 & P2 IAW VXIbus Spec. 8EA, Front Panel BNC Outputs 1 EA, Front Panel BNC Input
Cooling Requirements	watts/slot: 16 airflow/slot: 6 liter/sec @.05mm H_2O for 5°C Rise
Warranty	1 year

Instrument Specifications

Electrical Specifications

Outputs/Freq./Waveform*

1 ea/1 MHz sine, 4 ea/10 MHz sine, 2 ea/10 MHz TTL, 1 ea/1 PPS

Output Level/Load

Sine Output	1-2V P-P into 50 ohms
TTL Output	TTL compatible into 50 ohms
1 PPS Option	10V ± 10% into 50 ohms 5V option - CMOS compatible Rise Time 25 nsecs Fall Time 100 nsecs Pulse Width 16µs ± 100 nsecs

Optional Input (1PPS input can be used as a Synchronization signal) 1 PPS V_{OH}= 2.5V to 11V
V_{OLmax}= 0.8V
Pulse Width= 1µs min

Short Term Stability

1.0 Second (Allan Variance)$^{1/2}$	1E-10
10.0 Second (Allan Variance)$^{1/2}$	3E-11
100.0 Second (Allan Variance)$^{1/2}$	1E-11

1-Day Stability (25°C ± 3°C) 1E-10**

Frequency Aging Per Month (after 1 month of continuous operation) 5E-11

*Outputs can be configured at the factory with various combinations of frequencies available: 1 Hz (1 PPS output), and 0.1, 1, 5, and 10 MHz (sine or TTL). The total number of outputs is 8.

**Includes: Aging, Frequency Offset Over Temperature Range, setting accuracy at shipment and 10% Input Voltage change.

Instrument Specifications continued

Frequency Accuracy At Shipment	± 5E-11 (25°C)
Frequency Trim Range	± 1E-9 Minimum
Setting Resolution	1E-11
Isolation Between Outputs	≤ -80dB
Frequency Retrace (after 1 Hr Pwr On @ 25°C & up to 24 Hrs Pwr off)	5E-11

Phase Noise

1 Hz from Carrier	-70 dBc/$\sqrt{Hz}$
100 Hz from Carrier	-110 dBc/$\sqrt{Hz}$
1000 Hz from Carrier	-130 dBc/$\sqrt{Hz}$

Harmonic/Non-Harmonic Distortion (Sine Wave Output) -34 dBc/-65 dBc

Power Required

Voltage	No. of Pins Used	DC-Peak Current	Dynamic Current
+5	P1-3, P2-4	1.8A	1.0A
+12	P1-1	0.8A	0.5A
+24	P2-1	2A @ 0°C (for ≤5 min)	0.5A

Current At Turn On (0°C)
2.0 A Peak +24 Vdc for 5 minutes maximum

Input Voltage Sensitivity (For ± 10% Vdc Delta)	<5E-11
Warm-up Time	
Time to Lock (25°C)	≤4 minutes
Minutes/Frequency (25°C)	6 minutes/1E-9
Output Protection	Short Circuit Proof Reverse Polarity Protected

Front Panel LEDs

- RF Output Status Line, Red LED is on for output short circuit condition
- Rb Lock Status, Green LED will be on when Rb is locked
- Adjust Crystal Status, Yellow LED is on when Xtal voltage is out of range
- MODID Line, Green LED is on when the MODID is asserted
- POWER ON, Green LED is on when +24, +12, and +5 volts in the VRFS-MC are good

Environmental Specifications

Operating Temp. Range	0°C/+50°C (Ambient)
Freq. Offset Over Temp. Range	3E-10
Storage Temp.	-40°C to + 75°C
Magnetic Field Sensitivity	< 4E-13/AM^{-1} (worst case) (3E-11/gauss)
Relative Humidty	95%
EMC	IAW VXIbus Specification

VXIbus Specifications

Intelligence

Manufacturer ID	3938
Model Code	3840
Protocols*	EG, I, I4
Device Type	Message Based Servant
Address Space	A16 Only

8 bit Logical Address Switch
Static Configuration
Programmable Interrupter
Status/ID Register

*EG=Event Generation, I=VXIbus Instrument, I4=VXIbus 488.2 Instrument.

Commands

High Level Commands

:STATus:VERBose? The response for this command has the following format:

Rb Lock/Unlock,
Xtal Adj. Pass/Fail,
(RF Output Status),
Output #1 Pass/Fail,
....
Output #8 Pass/Fail,

:DELay<nn> This command sets the time delay between the input 1PPS and the output 1PPS. Delay is in seconds and the resolution is 100nsecs.

:DELay? The response for this command returns the delay value in seconds (±10nsecs accuracy). At power on the 1PPS output delay is set to within 100nsecs of the 1PPS input.

IEEE 488.2: Implements all mandatory common commands

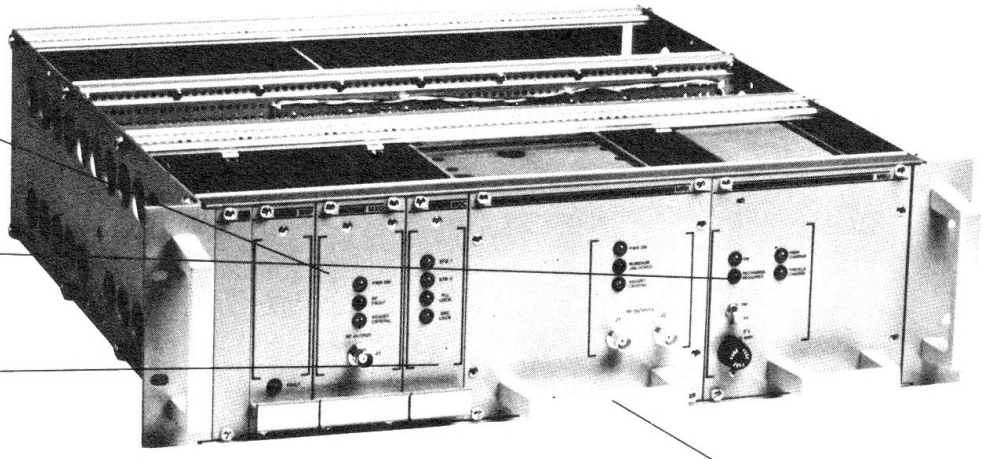
Ball Efratom Division

Ball Efratom Division, 3 Parker, Irvine, CA 92718-1605; Telephone (714) 770-5000; Telex 685-635; Fax (714) 770-2463
Ball Efratom Elektronik GmbH, Fichtenstr 25, 8011 Hofolding (Munich) Germany; Telephone 08104/9040; Telex 529701; Fax 08104/9918
Ball Efratom Corp., Ltd., P.O. Box 325, Bromley, Kent, BR1 2WX, England; Telephone 081-313 1078; Fax 081-290 6948

7/91

Ball Efratom Division

Efratom's Modular Frequency & Time Systems

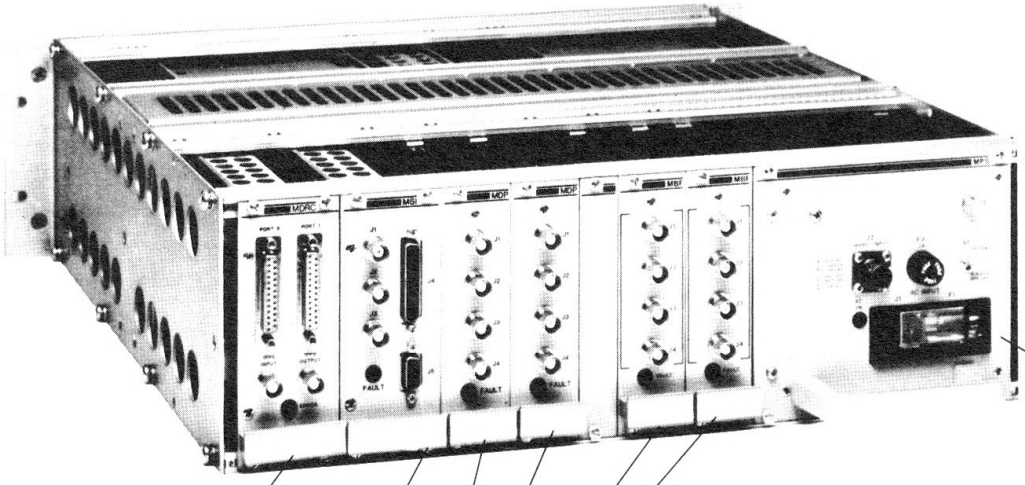


QUARTZ CRYSTAL OSCILLATOR (MXO)

BATTERY (MBU)

RUBIDIUM TO CRYSTAL OSCILLATOR FREQ. SYNCHRONIZER (MDC-RX)

RUBIDIUM OSCILLATOR (MRK)

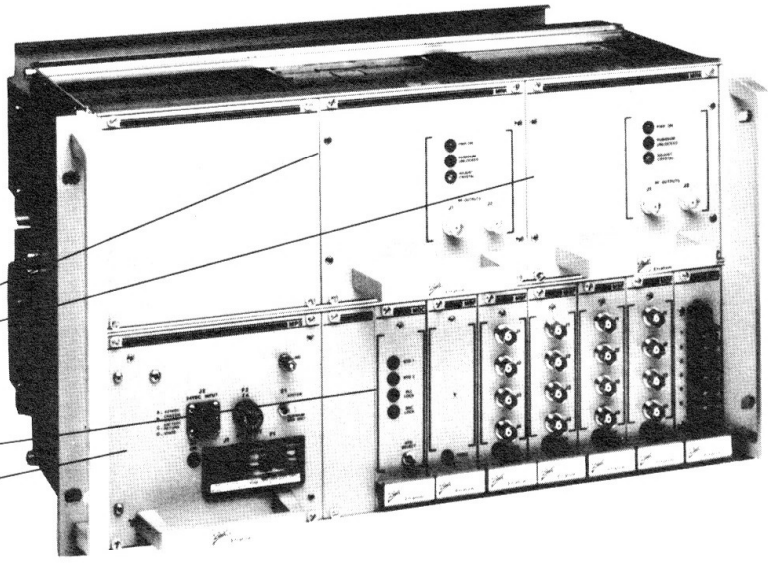


POWER SUPPLY (MPS)

DISCIPLINED Rb CONTROLLER FOR GPS (MDRC)

SYNTHESIZER AND INTERFACE (MSI) USED WITH TANS GPS RECEIVER

FREQUENCY DISTRIBUTION (MBF, MDP) 0.001, 0.01, 0.1, 1.0, 5.0, 10.0 MHz, 1-PPS



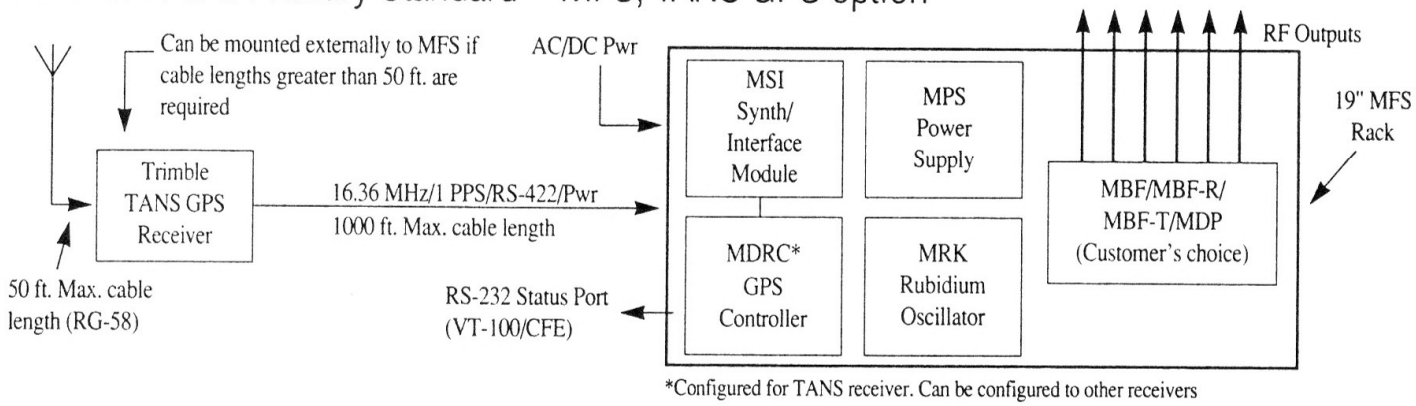
RUBIDIUM OSCILLATOR (MRK)

RUBIDIUM TO RUBIDIUM FREQ. SYNCHRONIZER (MDC-RR)

POWER SUPPLY (MPS)

Example Modular Systems Block Diagrams

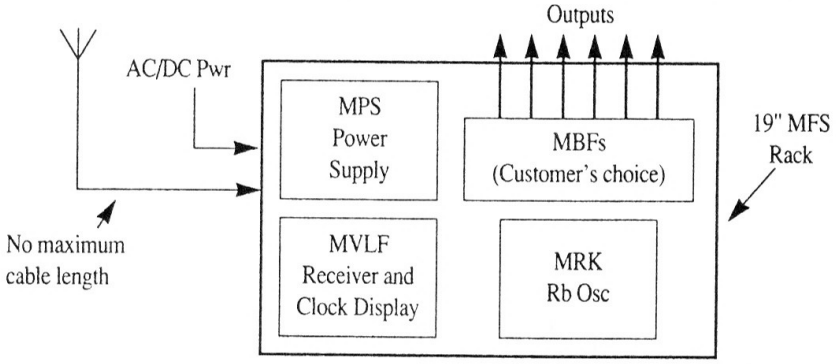
Alternative to a Primary Standard – MFS, TANS GPS option



*Configured for TANS receiver. Can be configured to other receivers

≤ 5E-12 Frequency Accuracy, ≤ 150 ns UTC Time Error (Selective availability disabled for at least one satellite)

Alternative to a Primary Standard – MFS, VLF/LF option

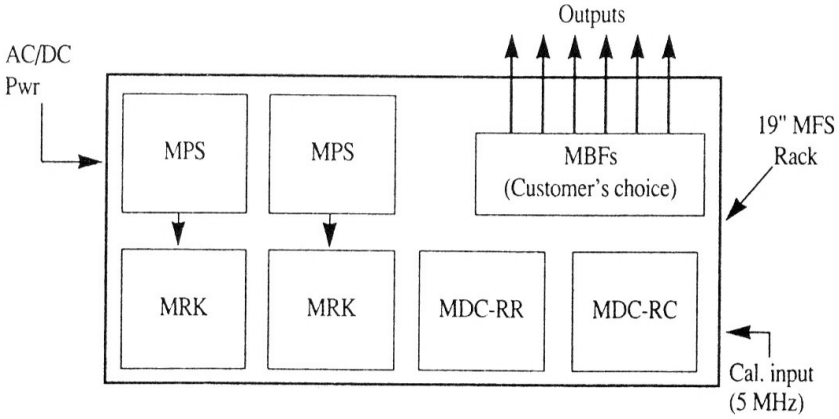


The MVLF uses nationally controlled/traceable low frequency transmitters (WWVB, MSF, DCF77, etc.) or the international Omega system to steer a Rb oscillator, providing an alternative to the GPS based system. (See MVLF module for details.)

1E-11 Frequency Accuracy, <1 μs UTC* Time Error with OMEGA

*UTC must first be set in MVLF

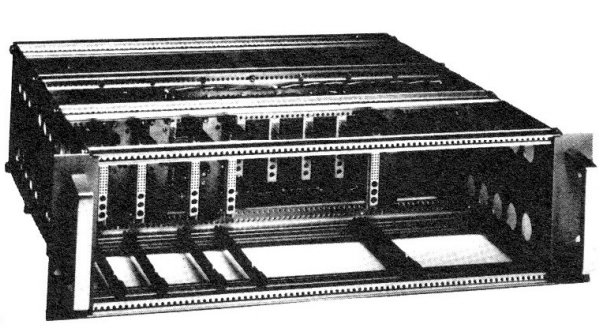
Redundant Frequency Generator, Calibrated by External Standard

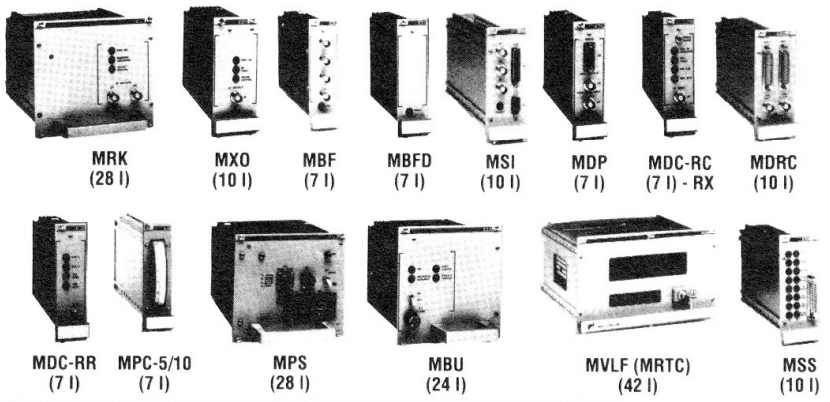


This MFS System phase locks the secondary MRK to the Master MRK. At failure detection of Master, secondary MRK is switched into MFS by the MDC-RR. The MDC-RC allows the Master MRK to be calibrated to an external standard. (The second MRK is automatically calibrated because it is phase-locked.)

1E-11/Mo. Freq. Aging, Ext. Cal. Rb (MRK) to ±5E-12, (-) 155 dBc @ 100 Hz (MRK-LN option)

Modular Frequency and Time Systems (MFS)





The Modular Frequency and Time System (MFS) provides the time and frequency industry with an innovative way to use a host of standard modules to form a 19 inch rack system. The main theme is as follows:

- Generate precise frequency and time through use of Rubidium Atomic Oscillators, Crystal Oscillators, and VLF/LF/GPS Receiver signals.
- Buffer and distribute frequency and time with virtually unlimited number of outputs at various frequencies.
- Automatic calibration of Rubidium Oscillators through use of external standards or VLF/LF/GPS receiver modules.
- Redundant systems based on independent or phase-locked oscillators.
- Battery backup to protect against ac power failure.

MFS Concept

The Efratom MFS is conceived as follows: The customer defines system requirements and contacts Efratom. Efratom will assist the customer in providing a custom solution to specific requirements. The custom MFS is based on the standard modules described in this brochure. The modules plug into the front and rear of a standard 19" rack, 5¼" high and 17½" deep. This unique feature doubles the available panel space to 32 inches of modules within the 19 inch rack. Optional chassis slides are available to provide access to the rear modules.

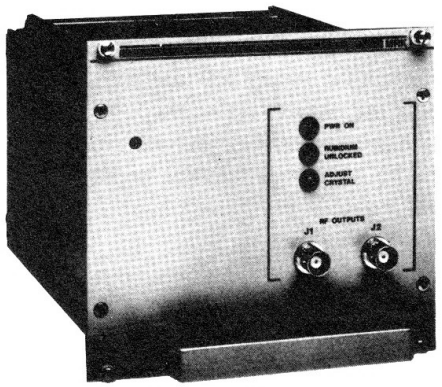
The module size is based on the DIN Euroboard system. The width of each module is specified in increments (I) and space not used is covered by blank panels. Each increment is equal to 7/10", a panel of 7(I) would fit into a 1.40" wide space in the rack chassis. The total width of the Efratom chassis is 80(I) front and 80(I) rear for a total usable space of 160(I). An 84(I) wide rack (168 total) is also available, if chassis slides are not used.

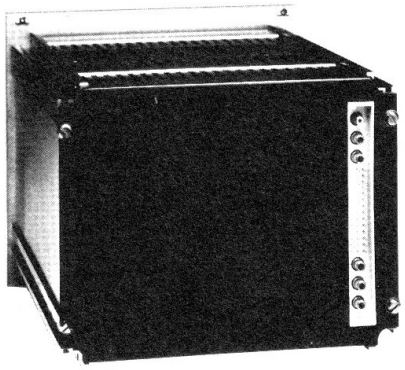
All modules interface with the rack using Cannon connector G06M426 series body with 6 RF or HV plug inserts, except the MSS Module, which uses a 96 pin connector. The connector pins for pin functions are not listed here but are shown in the operating manual for each module. The Cannon G06M426 series connector features 42 pins. The RF connectors used on the dress panels are BNC jacks.

Module	Width	Weight	Basic Function
MRK	28(I)	5.7 lb.	Rubidium Oscillator
MXO	10(I)	1.5 lb.	Quartz Crystal Oscillator
MBF	7(I)	1.2 lb.	Frequency Distribution
MBFD	7(I)	1.2 lb.	Frequency Distribution
MBF-T	7(I)	1.2 lb.	Frequency Distribution
MBF-R	7(I)	1.2 lb.	Frequency Distribution
MSI	10(I)	1.5 lb.	Synthesizer & Interface
MDP	7(I)	1.5 lb.	1 PPS Generation
MDC-RC	7(I)	1.2 lb.	Rubidium Oscillator Calibrator
MDRC	10(I)	1.5 lb.	Disciplined Rb Controller for GPS
MDC-RR	7(I)	1.5 lb.	Frequency Synchronizer RF switch
MDC-RX	7(I)	1.5 lb.	Frequency Synchronizer RF switch
MPC	7(I)+7(I)*	1.1 lb.	Phase Comparator
MPS	28(I)	9 lb.	Power Supply
MBU	24(I)	8 lb.	Battery
MVLF	42(I)+14(I)*	4.4 lb.	VLF/LF Frequency and Time Receiver
MRTC	42(I)+7(I)*	4.4 lb.	Real Time Clock and IRIG Code Generator
MSS	10(I)	1.5 lb.	System Status

*Connector Panel

Frequency Generators – MRK, Rubidium Oscillator

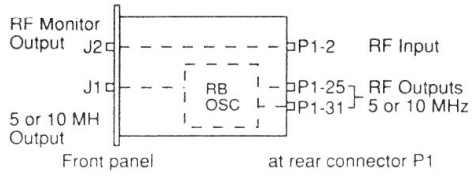




The Modular Rubidium Oscillator, Model MRK is the primary frequency generating source of the EFRATOM MFS. It provides a 5 or 10 MHz sinusoidal output frequency of excellent short- and long-term stability over a wide range of environmental conditions. This superior stability is achieved by locking an internal crystal oscillator to the ground state hyperfine transition of ^{87}Rb. The module is designed to interface to all other MFS modules through the rear connector. The MRK contains the well proven, field tested Model FRK Rubidium Frequency Standard.

Model #	Output Characteristics
MRK-1AOC1	L, 10 MHz
MRK-2AOC1	H, 10 MHz Low Aging
MRK-3AOC2	LLN, 5 MHz Low Noise
MRK-4AOC2	HLN, 5 MHz Low Noise, Low Aging
MRK-3AOC1	LLN, 10 MHz Low Noise
MRK-4AOC1	HLN, 10 MHz Low Noise, Low Aging

RF Signal Diagram



The "Monitor" output is brought through the module from another rf source which is injected at P1-2. This rf signal may originate from a MBF module.

The MRK has 2 rf outputs at the rear connector and one rf output at the front dress panel which are 5 or 10 MHz depending upon model selected.

Electrical Specifications

RF Output 5 or 10 MHz Sinewave
0.5 ± 0.1 Vrms into 50 Ohms
Frequency set to within ± 5E -11 at shipment

Aging	L	4E-11/month
	H	1E-11/month
Short-Term Stability	L	3E-11 ($\tau^{-1/2}$) for 1 sec < τ < 100 sec
	H	1E-11 ($\tau^{-1/2}$) for 1 sec < τ < 100 sec
Temperature Coefficient	L	3E-10 over MFS temp range
	H	1E-10 over MFS temp range

Phase Noise, SSB (1 Hz BW), See Figure 1			
	Output	**Hz from carrier**	**-dBc / √Hz**
L	10 MHz	100	120
H		1000	145
LLN	5 MHz	100	155
HLN		1000	155
LLN	10 MHz	100	147
HLN		1000	147

Warm Up 10 minutes to reach 2E-10 at 25°C ambient

Harmonic / Non-harmonic 40 dB down / 80 dB down

Trim Range 2E-9

Retrace 2E-11 (after 1 hr pwr on @ 25°C and up to 48 hrs pwr off)

Magnetic Field 4E-13 / Am^{-1}, or 3E-11 / 0.1 militesia

Altitude 1E-13 / mbar from sea level to 40,000 ft.

Power Input Electronics 20.5 Vdc, 9 W
Heater 18.5 Vdc Minimum, 30 W warm-up
5 W at 25°C
10 W at -25°C

Led Indicators on Front Panel

Pwr On	(Grn)	Normally ON
Rubidium Unlocked	(Red)	Normally OFF ON if Rubidium out of lock
Adjust Crystal	(Yel)	Normally OFF ON when calibration required

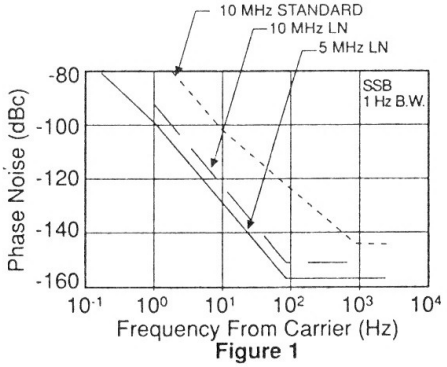
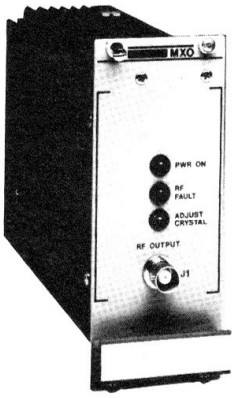
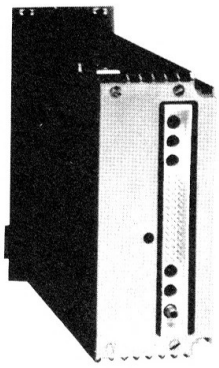


Figure 1

Frequency Generators, – MXO, Quartz Crystal Oscillator

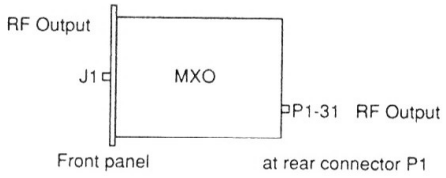




The Modular Crystal Oscillator, Model MXO, is a highly stable 10 MHz Voltage Controlled Crystal Oscillator, and is based on a high quality, 3rd overtone, AT-cut quartz oscillator. To improve its stability over temperature, the crystal and the oscillator are thermostatically controlled. Its good performance and low cost make the MXO ideally suitable as a backup oscillator in a redundant MFS. As with any crystal oscillator, its aging characteristics will greatly improve if operated continuously.

Model Number	Description
MXO 0A0C1	10 MHz Sinewave

RF Signal Diagram



Electrical Specifications

RF Output 10 MHz Sinewave 0.5 ± 0.1 Vrms
into 50 Ohms
One output at front dress panel
One output at rear connector

Warm Up 60 minutes to 2E-8 (as compared to frequency after 24 hrs)
15 minutes to 5E-7

Aging 1E-6/year

Short-Term Stability 1E-11 for $\tau = 1$ sec

Phase Noise
SSB (1 Hz BW) -120 dB at 100 Hz from carrier
-135 dB at 1 kHz from carrier

Harmonic/
Non-Harmonic 30 dB down / 100 dB down

Trim Range 2E-6 typical

Load Dependence ± 2E-10 for 10% load change

Temp Coefficient 3E-8, -25° C to 50° C

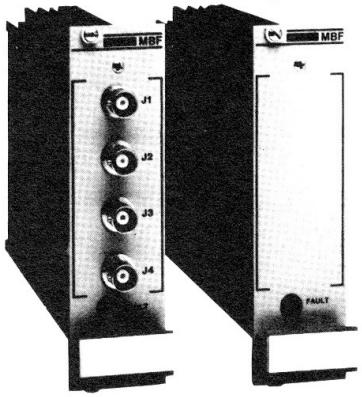
Power Input 20.5 Vdc, 13 W warm-up
5 W at 25° C, 9W at -25° C

Led Indicators on Front Panel

PWR On	(Grn)	Normally ON
Rubidium Unlocked	(Red)	Normally OFF ON if Rubidium out of lock
Adjust Crystal	(Yel)	Normally OFF ON when calibration required

Frequency Distributors

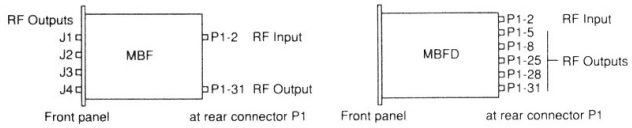
MBF and MBFD Frequency Distribution



The Modular Frequency Distribution unit, Model MBF, provides (4) outputs of 0.1, 1.0, 5.0, or 10 MHz derived from the primary RF Oscillator (MRK or MXO) within the MFS chassis. The MBFD has (5) outputs used to distribute RF within the 19" rack (consult factory for MBFD usage). Both the MBF and MBFD contain fault monitor circuits which will alert the user if one or more of its outputs fail or if the input signal drops below minimum drive levels.

MBF Model	Input/Output	MBFD Model
MBF-OA1C1 MBF-8A1C1	10 MHz / 10 MHz	MBFD-OA1C1
MBF-OA1C2 ----------	10 MHz / 5 MHz	----------
MBF-OA1C3 ----------	10 MHz / 1 MHz	----------
MBF-OA1C4 ----------	10 MHz / 0.1 MHz	----------
MBF-OA2C1 ----------	5 MHz / 10 MHz	----------
MBF-OA2C2 MBF-8A2C1	5 MHz / 5 MHz	MBFD-OA2C1
MBF-OA2C3 ----------	5 MHz / 1 MHz	----------
MBF-OA2C4 ----------	1 5 MHz / 0.1 MHz	----------

RF Signal Diagram



Electrical Specifications

RF Input 5 or 10 MHz
MBF-0XXXX 0.4 to 0.6 Vrms, 50 Ohm input impedance
MBF-8XXXX 0.4 to 0.6 Vrms, > 1K Ohm input impedance
MBFD-0XXXX 0.15 to 0.6 Vrms, 50 Ohm input impedance

RF Output (4) each 0.1, 1.0, 5.0, or 10.0 MHz
MBF 1 Vrms into 50 Ohms, each adjustable from 0.5 to 1.5 Vrms
MBFD 0.5 ± 0.1 Vrms into 50 Ohms

Isolation -55 dBc between outputs, -90 dBc between modules
-80 dBc between outputs – available

Harmonic -34 dBc

Phase Noise

MBF/MBFD	(-dBc / √Hz) at 100 Hz	(-dBc / √Hz) at 1000 Hz
MBX -XA1C1	-147 (LN MRK) -120 (STD MRK)	-147 (LN MRK) -145 (STD MRK)
MBX -XA2C1	+9 dBc above input	+9 dBc above input
MBX-XA2C2	-155	-155

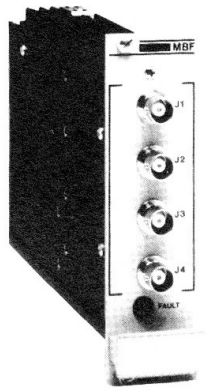
When an MDC-RX or MDC-RR is used in the system, contact the factory for potential effects on the phase noise floor.

Short Circuit Proof Outputs

Power Input 20.5 Vdc, 3 W

LED Indicators on Dress Panel RF Fault (R)

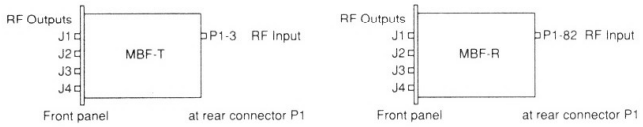
MBF-T and MBF-R Frequency Distribution



The Modular Frequency Distribution units, Model MBF-T and Model MBF-R provide up to four (4) TTL (MBF-T) or EIA RS-422 (MBF-R) compatible outputs derived from a 10 MHz primary RF oscillator (MRK or MXO) within the MFS chassis. Standard output frequencies are 0.001, 0.01, 0.1, 1.0, or 5.0 MHz; however, combinations of these frequencies are available upon request. Each buffer module contains fault indicator circuitry which will alert the user if one or more of its outputs fail or if the input signal drops below minimum drive levels.

MBF-T Model	RF Input/Output	MBF-R Model
MBF-T-OA1C2	10 MHz in / 5 MHz out	MBF-R-OA1C2
MBF-T-OA1C3	10 MHz in / 1 MHz out	MBF-R-OA1C3
MBF-T-OA1C4	10 MHz in / .1 MHz out	MBF-R-OA1C4
MBF-T-OA1C5	10 MHz in / .01 MHz out	MBF-R-OA1C5
MBF-T-OA1C6	10 MHz in / .001 MHz out	MBF-R-OA1C6

RF Signal Diagram



Electrical Specifications

RF Input 10 MHz
0.4 to 0.6 Vrms; 50 Ohm input impedance

RF Output (4) each 0.001, 0.01, 0.1, 1.0, or 5.0 MHz

MBT TTL compatible into 50 Ohm load; 50% Duty Cycle; 20 nsec Max Rise Time and Fall Time.

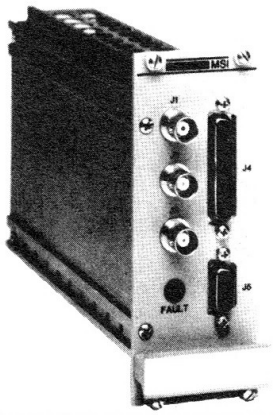
MBR RS-422 compatible into 100 Ohm load; 50% Duty Cycle; 20 nsec Max Rise Time and Fall Time.

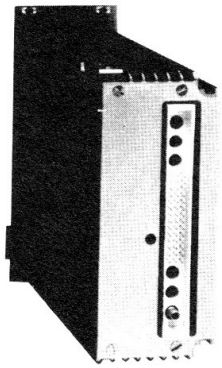
Short Circuit Proof Outputs

Power Input 20.5 Vdc, 5.0 W

LED Indicators on Dress Panel RF Fault (R)

Frequency Distributors – MSI, Synthesizer and Interface

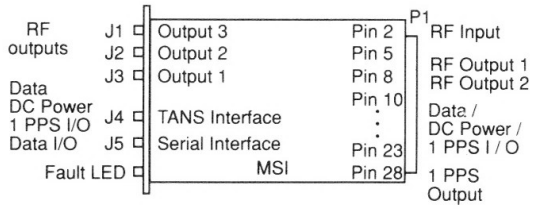




The Modular Synthesizer and Interface, Model MSI, accepts a 10 MHz frequency reference and generates octave multiples of 1.023 MHz or 1.024 MHz, with a maximum multiplication factor of 16. Three outputs are available in sine or TTL format. The MSI module is designed primarily to serve as an interface between the MFS and the Trimble TANS GPS receiver as part of Efratom's GPS option to the MFS. In addition to providing the necessary RS-232 and 1 PPS interfaces, the module generates the rf (16.368 MHz) and dc inputs that are required by the TANS receiver. The MSI will output the time of day (ASCII format) information from the MDRC via the RS-422 interface port (J5). The excellent performance of the module, however, makes it suitable for use in other applications as a general-purpose frequency synthesizer. A LED indicator on the dress panel indicates module fault.

MSI Model	Input	Output 1	Output 2	Output 3
MSI-101	10 MHz	16.368 MHz	1.023 MHz TTL	2.046 MHz TTL
MSI-102	10 MHz	16.368 MHz	1.024 MHz TTL	2.048 MHz TTL

Signal Diagram



Electrical Specifications

RF Input 10 MHz, 0.5 ± 0.1 Vrms into 50 ohms

1 PPS Input
Signal Level: Differential 1 PPS, RS-422 spec compatible
Polarity: Negative
Pulse Width: 10 nsec minimum

RF Outputs* 1.023 MHz x N or 1.024 MHz x N (N=1, 2, 4, 8, 16)

Signal Level
Sine Wave: 1 Vrms into 50 ohms, minimum
TTL: TTL compatible into 50 ohms

Phase Noise -70 dBc at 1 Hz
SSB (1HzBW) -110 dBc at 100 Hz
-130 dBc at 1000 Hz

Harmonic Distortion -40 dBc (sine wave only)

Non-Harmonic Distortion -70 dBc

1 PPS Outputs*
Signal Level TTL compatible into 50 ohms

Polarity Positive

Pulse Width Programmable,
1 µsec to 126 µsec
0.5 µsec steps

Switching Characteristics (typical)
Rise Time < 25 nsec
Fall Time < 100 nsec

Input Power (dc output unloaded)
20.5 Vdc, 8 W at +25°C steady-state

RS-232 Interface (on board)
Inputs/Outputs: RS-232 compatible

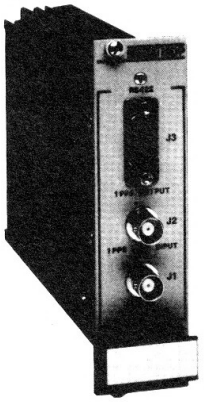
RS-422 Interface (on board)
Inputs/Outputs: RS-422 compatible

LED Indicator on Front Panel
Module Fault: (Red)
Normally OFF

Mechanical Specifications
Width: 10 units
Connectors: J1, J2, J3 BNC
Connector J4: DB-25S
Connector J5: DB-9S
Connector P1: Cannon G06M426P4BEBL

*Short circuit protected

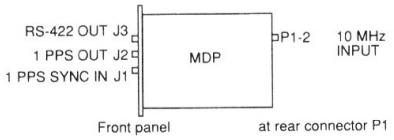
Frequency Distributors
MDP, 1 PPS Generation



The Modular Digital Pulse, Model MDP provides multiple 1 PPS outputs (1 PPS at J2 and RS-422 at J3). When used in conjunction with an external 1 PPS signal, the MDP automatically synchronizes its 1 PPS outputs to within ±100 nanoseconds of the external signal. Synchronization is indicated by the "SYNC" LED which blinks until the external signal is removed. The internal 1 PPS is derived from the MFS primary oscillator.

Model Number	1 PPS Characteristics J2
MDP-OA1CO	Amplitude: 10 Volts ±10% peak into 50 Ohms

Signal Diagram



Electrical Specifications

Inputs * 10 MHz Sinewave
0.5±0.1 Vrms (REF input from MRK or MBF)
1 PPS SYNC (input J1)
3.5 to 11 Volts peak
Width ≥ 2.0 µsec
Rise Time ≤ 20 nsec

Outputs (1 PPS J2, J3)
Width 20 ± 2 µsec
Rise Time ≤ 20 nsec
Fall Time ≤ 100 nsec
Jitter ≤ 10 nsec
RS-422 balanced driver output (J3)
EIA RS-422 compatible

Power Input 20.5 Vdc, 3 W

LED Indicators on Front Panel
SYNC (green) Synchronization

Connectors on Front Panel
J1 & J2 BNC Jack
J3 M24308 / 3-1 or equiv.

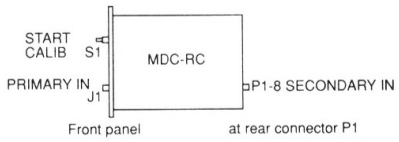
* 50 Ohm input impedance

Frequency Calibrators
MDC-RC, Rubidium Osc. Calibrator

The Modular Rubidium Oscillator Calibrator, Model MDC-RC, calibrates the MRK Rubidium oscillator via a temporarily connected 5 MHz Cesium Frequency Standard. The Primary Standard is connected to the MDC-RC connector (J1), The "START CALIB" button is pressed, and the Secondary Standard (the MRK) is syntonized to ±5E -12 of the Primary Cesium reference. When calibration is complete, (approximately 90 minutes) the C-field control voltage signal is held in memory until the next calibration cycle. The external reference Standard must be equal to or better in noise characteristics than the MRK; Option 004 Cesium Standard is recommended.

Model Number	Primary Input / Secondary Input
MDC-RC-A1CO	5 MHz Cs / 10 MHz Rb
MDC-RC-A2CO	5 MHz Cs / 5 MHz Rb

Signal Diagram



Electrical Specifications

Primary RF Input (J1 Front Panel Input)
Cesium Standard 5 MHz Sinewave
0.4 to 1.0 Vrms, 50 Ohm input impedance

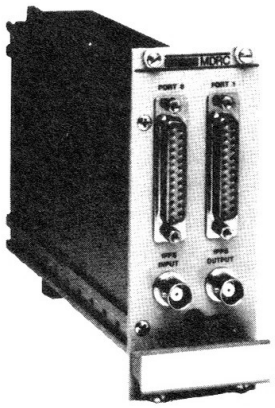
Secondary RF Input (Internal MFS connection to MRK)
Rubidium Standard 5 or 10 MHz Sinewave
0.5 ± 0.1 Vrms, 50 Ohm input impedance

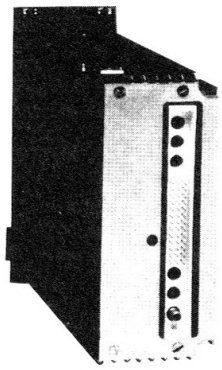
Calibration (MRK)
Calibration Accuracy ± 5E -12
Calibration Time Approximately 90 minutes
Trim Range 2E -9
Resolution Approximately 5E -13 (LSB)

Power Input 20.5 Vdc, 3 W

LED Indicators on Front Panel
Cal In Progress (Grn) ON during calibration
Cal Fault (Red) ON during warm up until MRK locks; also if external std is outside the track-and-hold range
Pri Std (Grn) ON when external std is connected
Sec Std (Grn) ON when secondary std is connected

Frequency Calibrators – MDRC, Disciplined Rb Controller for GPS





The Modular Disciplined Rb Controller for GPS, Model MDRC has the standard firmware designed to interface with a Datum 9390-5100, or an Osborne TTR-6, or the Trimble TANS Receiver. When the Trimble TANS receiver is used, the Model MSI must be used as an interface between the MFS rack and the TANS GPS receiver. It will also work with the corrected 1 PPS output of any GPS receiver of similar accuracy providing the receiver generates a flag when its 1 PPS signal is derived from a valid satellite signal.

When the MDRC is installed with a power supply (MPS), a Rubidium Oscillator (MRK), and a GPS receiver, the user is provided with very precise time and frequency traceable to UTC (USNO / NIST). It communicates with the GPS receiver and the user via RS-232 interfaces. It further requires a 1 PPS input from a GPS receiver to discipline the 10 MHz signal from the rubidium oscillator (MRK), removing oscillator aging. The MDRC will also improve the temperature coefficient of the MRK by a factor of about 4.

The NAVSTAR / GPS (Global Positioning Satellite System) is a satellite-based radio navigation system consisting of a constellation of satellites in 12 hour orbits. It is designed to provide global navigation capability to users 24 hours a day. At the present time, GPS is not fully operational for 3D, 24 hour global navigation, but is fully operational for use in a MDRC based time and frequency system. During satellite visibility periods, the MDRC uses GPS Receiver's 1 PPS or data port phase error data to develop necessary compensation data for the rubidium oscillator, which "flywheels" while satellites are absent.

The MDRC provides a standard 1 PPS output (BNC connector) and two RS-232 ports (25 pin, D-sub) all on the front panel. Port 0 is used to interface with the receiver and Port 1 may be used to report MDRC / MRK / Receiver status via any DEC VT-100 compatible display terminal. Time of day information, day of week: hrs: min: sec, is available over the RS-232 port 1 in an ASCII format.

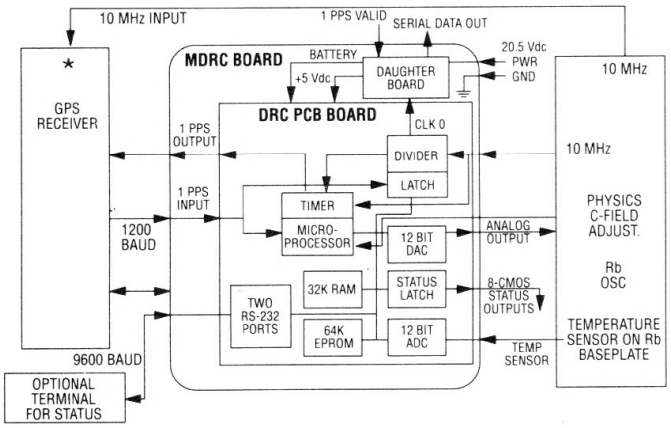
The MDRC controlling a rubidium oscillator can provide a true alternative to a Cesium standard in stationary applications. It features lower hardware cost, lower life cycle cost, excellent short-term stability, better phase noise and precise time, all traceable to USNO / NIST.

The common view technique can be used for time comparisons between two sites tracking the same satellite, which allows for synchronization accuracies below the 10 nanosecond level depending on the quality of the GPS receiver being used.

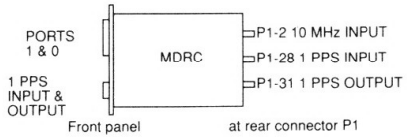
In the telecommunications industry, digital communications techniques require very precise frequency coordination between nodes. In the past, Cesium standards were used exclusively as Stratum-I sources in T1 networks.

Now with the MDRC / GPS system, the telecommunications industry can meet or exceed the performance of the cesium at less expense. The MDRC / GPS system is combined with the other modules in the Efratom MFS to provide battery back-up (MBU), buffered outputs of 0.1, 1.0, 5.0, and 10 MHz, as well as 2.048 MHz (MBF and MSI). Provides a versatile primary frequency distribution system for stationary applications.

Frequency Calibrators – MDRC, Disciplined Rb Controller (continued)



Signal Diagram



Electrical Specifications

1 PPS Output
CMOS / TTL Compatible Positive edge synchronous 3.5 - 5.5 volts, 50 ohms

Width	16 µs ± 1 µs (50% points)
Rise Time	< 25 nsec (10% to 90%)
	< 10 nsec (.8 to 2.8 volts)
Fall Time	< 100 nsec (90% to 10%)
Jitter	< 2 nsec rms; < 10 nsec max

Can be synchronized within ± 100 nsec of an external pulse

1 PPS Input
CMOS / TTL Compatible
2 - 10 volts peak, 50 ohms
Positive edge sensitive
100 ns accuracy (single measurement)
Dynamic range 4 µs/s maximum drift rate

10 MHz Input
10 MHz, 0.5 ± 0.1 Vrms to 2.0 Vrms into 50 ohms (from MRK)

Analog Output
0 to 5 volts (12-bit DAC)
Approximately 4.88E-13 per count resolution (with 2E-9 rubidium tuning range).

Data Input/Output
Two RS-232 ports, 9600 baud for Port 1, 1200 baud for Port 0

Status Outputs
Eight CMOS outputs for status
MDRC sync LED on front panel (bit 0)

On Internal Conn:
bit 0 – 1 PPS Sync Error
bit 1 – CPU OK (pulsed)
bit 2 – RAM OK
bit 3 – EPROM OK
bit 4 – Rb Osc Sensitivity Not OK
bit 5 – Satellite Track or Ref. 1 PPS Stat
bit 6 – not used
bit 7 – not used

Power
20.5 Vdc, 4.5 W

Connectors

On front panel
1 PPS signals – BNC (Amphenol 31-2221)
RS-232 signals – D-sub, 25-pin

Internal (P1)
Cannon G06M426P4BEBL

Time & Frequency Performance

Start-up*	**Selective Availability**	
	Active	**Inactive**
Frequency accuracy after 3 days	≤2E-11 (UTC)	≤2E-11 (UTC)
Frequency accuracy at 4 days	≤1E-11 (UTC)	≤5E-12 (UTC)

Long-term Stability* (4 or more days after startup)

Frequency accuracy	≤1E-11 (UTC)	≤5E-12 (UTC)
1 PPS accuracy	≤1 µsec (UTC)	≤150 nsec. (UTC)

*Performance verified with specified Datum, Osborne, and Trimble TANS receivers. Temperature fluctuations 5°C max/day. Startup performance based on 12 hrs. continuous tracking per day.

Options

MDRC-A1C3-XXX with Cannon connector
MDRC-A1D3-XXX with DIN connector

Temperature coefficient
4 to 1 improvement over typical rubidium standard specification, using Efratom Model MRK. (See below for XXX numbers.)

Osborne TTR-6 Receiver Firmware Interface	-007
With temp. coefficients programmed	-T07*
Datum 9390-5100 Receiver Firmware Interface	-009
With temp. coefficients programmed	-T09*
Trimble TANS Receiver Firmware Interface	-011
With temp. coefficients programmed	-T11*

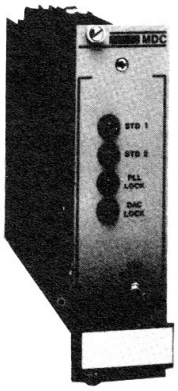
Regular 1 PPS Mode option:

For 1 PPS mode applications including Block II satellites with Selective Availability	-010
With temp. coefficients programmed	-T10*

*Must be ordered with MRK – P/N MRK-2A3C2-60

Frequency Synchronizers / RF Switches

MDC-RR, Rubidium to Rubidium



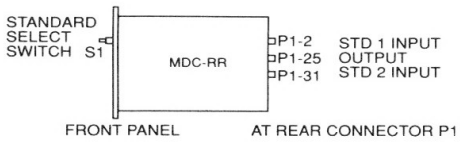
The Modular Rubidium to Rubidium synch/RF Switch, Model MDC-RR, functions as an RF switch or as a Phase Lock Loop (PLL), capable of locking two MRK frequency sources. In the RF switch mode, the MFS becomes a redundant system based on two fully independent frequency sources. In this mode however, up to .2 microsec time error can occur at the time of the switch-over. In the PLL mode the error is reduced to less than 10 nanosec; however, the STD 2 MRK is not fully independent of the STD 1 MRK.

The tradeoff between the two basic configurations depends on the system specification. Efratom is pleased to assist potential customers in their system evaluations.

In either case, the MDC-RR will, during initial turn-on, select the first locking MRK as the primary standard (driving the system). A front panel pushbutton allows the operator to select either MRK as the primary standard as STD 1 or STD 2. The system will always select the alternate standard if the standard selected has an anomaly indicated by the oscillator's BITE signal.

Model Number	Description
MDC-RR-A1C1	10 MHz Rb / 10 MHz Rb
MDC-RR-A2C2	5 MHz Rb / 5 MHz Rb

Signal Diagram



Electrical Specifications

RF Input 5 or 10 MHz Sinewave
0.5 ± 0.1 Vrms, 50 Ohms input impedance
STD 1 and STD 2 must be same frequency, isolation > 80 dBc

RF Input 5 or 10 MHz (same as input frequency)
-8.5 dBc nominal loss

Short-Term Stability and Phase Noise
Determined by the primary oscillator driving the MDC. Except the MRK Low Noise Option, > 140 dB @ 100 Hz, >150 dB @ 1 kHz from the carrier

Phase Error at Switchover

PRIME to BACKUP < 10 nanoseconds, PLL mode
BACKUP to PRIME < .2 microsecond

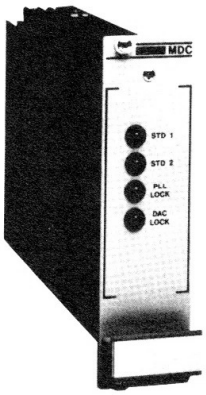
Syntonization Error < 5E-12

Power 20.5 Vdc, 2W

LED Indicators on Front Panel

Std 1	(Grn)	Pll Lock	(Grn)
Std2	(Grn)	Dac Lock	(Grn)

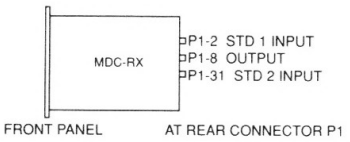
MDC-RX, Rubidium to Crystal



The Modular Rubidium to Quartz osc. synch/RF Switch, Model MDC-RX functions as a RF switch or as a Phase Lock Loop (PLL) synchronizer of a Rubidium Frequency Standard (MRK) and an MXO Crystal Oscillator to for a redundant system. Since the MRK is an atomic oscillator, the system will always use the MRK as the primary and the MXO as the backup. The MXO is syntonized to the MRK via the MXO xtal control voltage. Phase lock of the two oscillators occurs within 2 minutes after atomic lock is achieved on the MRK (typically 6-8 min after turn-on). When an MRK fails, the MDC-RX automatically switches to the MXO with a time error of < 10 nanoseconds. The system will not continue in an MRK spec manner, but will assume the MXO spec. The MXO provides an excellent lower cost backup oscillator to support the system until the MRK can be replaced. A failed unit can be removed without affecting the system operation. When the repaired MRK is reinserted, the MDC-RX will automatically switch from the backup MXO mode to the newly calibrated MRK.

Model Number	Primary Input / Secondary Input
MDC-RX-A1C1	10 MHz rb / 10 MHz XTAL

Signal Diagram



Electrical Specifications

RF Input 10 MHz Sinewave
0.5 ± 0.1 Vrms, 50 Ohms input impedance
STD 1 and STD 2 must be same frequency, isolation > 80 dBc

RF Input 10 MHz (same as input frequency)
-8.5 dBc nominal loss

Short-Term Stability and Phase Noise
Determined by the primary oscillator driving the MDC. Except the MRK Low Noise Option, > 140 dB @ 100 Hz, >150 dB @ 1 kHz from the carrier

Phase Error at Switchover

PRIME to BACKUP < 10 nanoseconds

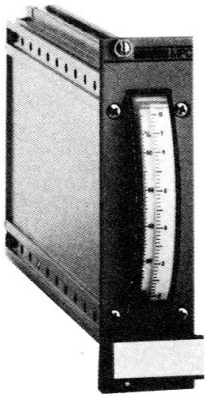
Syntonization Error < 5E-10

Power 20.5 Vdc, 2W

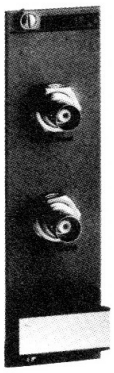
LED Indicators on Front Panel

Std 1	(Grn)	Pll Lock	(Grn)
Std2	(Grn)	Dac Lock	(Grn)

Frequency / Phase Comparison – MPC, Phase Comparator



MPC
MODULE



MPC
SEPARATE
CONNECTOR
PANEL

The Modular Phase Comparator, Model MPC, accepts as a reference signal a 5 or 10 MHz signal generated by the MRK or MXO. The input to the MPC comes from the unit under test (UUT) which can be 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 MHz. The resultant phase comparison of the reference and the UUT is displayed on the MPC front panel meter. The phase comparison can also be displayed on an external recorder through a 0 to 10 Vdc output. Both the UUT input connector and the recorder output connector are located on a separate connector panel, usually located next to the MPC module.

Model Number	Description
MPC-OA1CO	10 MHz Reference
MPC-OA2CO	5 MHz Reference

Electrical Specifications

Outputs

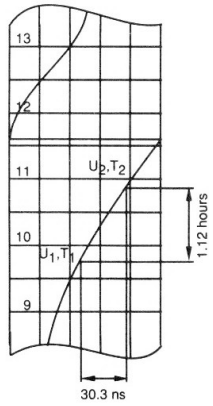
Front Panel Meter	0-10 Incremented scale with zero phase error, the pointer is at 5 (mid-scale) Meter accuracy ± 5% at full scale deflection
Deflection Yields	-100 to +100 nsec (5 MHz REF) -50 to +50 nsec (10 MHz REF)
Connector Panel Recorder Output	0 to 10 Vdc Full-scale
Alarm Output	TTL / CMOS compatible

Inputs

REF Input	5 MHz; 10 MHz 0.5 ± 0.1 Vrms 50 ohm Input Impedance
UUT Input	1, 2, 3, 4, 5, 6, 7, 8, 9 or 10 MHz 0.4 to 1.5 Vrms 50 ohm Input Impedance
PWR Input	20.5 Vdc Regulated to ± 5%, 1.5W

Application Note:

The measurement of extremely small frequency differences encountered when using high precision quartz and atomic oscillators is most commonly done by comparing the phase between two sources. The frequency difference may then be calculated as the first derivate of phase-over time. In practice this is done by watching the phase meter for some period of time and determining the associated phase change or by determining the time interval for a particular phase change using a stop watch. A more convenient way, particularly if very small frequency differences are to be expected, is to record the phase on strip chart recorder. The figure shows a typical record and gives an example of how to interpret it.



U	Recorder Voltage
φ_{REF}	Reference Phase
φ_{UUT}	Unit Under Test Phase
f_{REF}	Reference Frequency
y	Normalized Frequency Departure of UUT
T	Measurement Time Interval

$\varphi = \varphi_{UUT} - \varphi_{REF}$

$U = 10V \cdot \varphi / (2 \cdot \pi \cdot f_{REF}) + 5V$

$Y = (\varphi_2 - \varphi_1) / (T_2 - T_1) / (2 \cdot \pi \cdot f_{REF})$

$Y = (U_2 - U_1) / (10V \cdot f_{REF}) / (T_2 - T_1)$

Example

$U_1 = 4.67V$

$U_2 = 7.70V$

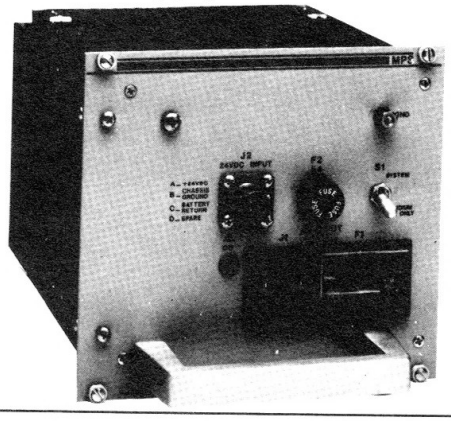
$T_2 - T_1 = 1.12h = 4032s$

$y = (7.70V - 4.67V) / (10V \cdot 10\ MHz) / 4032s$

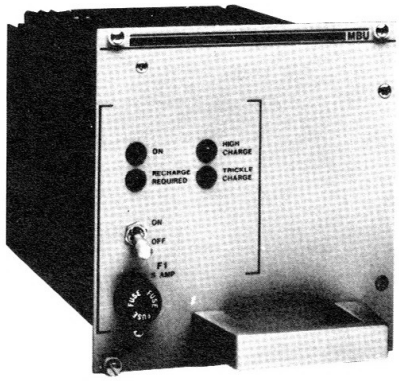
$y = 30.3ns / 4032s = 7.5E\text{-}12$

Power Supplies

MPS, Power Supply



MBU, Battery



The Modular Power Supply, model MPS, is designed for use in the Efratom modular system. The unit will operate from an AC or DC input and supplies power to the other units within the rack assembly. "Priority switching" is employed in the MPS module. When AC, DC, and Modular Battery Unit, model MBU inputs are present, the MPS selects AC as long as the AC input voltage requirements are met. The DC input will power the MPS when the AC fails to meet the requirements or is disconnected. The MBU input will be selected when both AC and DC inputs fail to meet the requirements.

The MPS provides filtering, rectification, and regulation of the input and supplies 20.5 Vdc regulated and 23-33 Vdc unregulated power for the MFS electronics. The MPS also supplies heater power to the Rubidium Oscillator (MRK) and low voltage AC power to the MBU module for battery charging.

The MPS can be used in conjunction with a MBU module, to provide full system performance during an AC power failure. A manual switch minimizes power drain during transport by powering down non-essential modules.

Model Number	Description
MPS-OAOCO	Standard Power Supply

Electrical Specifications

Power Input 100, 120, 220, 240 VAC
Voltage selector and fused connector at J1
Line V +10% / -15%, 48-440 Hz, 200 W max.
22.5 to 32 Vdc, 6 A at J2
23 to 29 Vdc at P1-25, MBU input

Power Output Supplied to MFS rack assembly at P1
Regulated 20.5 Vdc, 55 W, 3.5 m Vrms Ripple
Unregulated 23-33 Vdc
-12V @ 0.5 W, +5V @ 2.5 W
Max total current for outputs is 5.0 A (6.0 at warm-up)

Heater Power (2 outputs) Supplied to MRK
18.5 to 31 Vdc
40 W max for 10 minutes (warm-up), 20 W steady state
5 m Vrms max Ripple when regulated mode (after warm-up)

Outputs are short circuit protected.
DC Input protected against reversed polarity.
AC and DC inputs are fused.
Power Connectors
DC input at J2 Cannon KPTO2E*-4P
AC Input at J1 IEC Connector (Cable supplied)
LED Indicators on Front Panel
AC On (Red) On with AC PWR on

The Modular Battery Unit, model MBU, is a standby power source designed to complement the MPS and provide an uninterrupted DC power to modules in the MFS in the event of an AC power failure. The MBU provides a nominal 24 Vdc (2.5 Ah) via a rechargeable battery pack. The MPS provides low voltage AC power to the MBU as long as AC power is applied and switches the MBU's output on-line when an AC power failure occurs. For most system configurations an hour of backup power will be realized.

Model Number	Description
MBU-0A0C0	Standard Battery Module

Electrical Specifications

Power Input 35 VAC, 0.4 Amp, from Modular Power Supply (MPS)

Power Output 24 Vdc nominal, 45 Watt hours nominal

Battery Pack The battery pack consists of twelve, 2 Vdc, 2.5 Ah batteries wired in series. GATES #0810-0004 (sealed lead acid)

Electrical Protection AC input and DC output fused.

Recharge Times 10 hours for 90% capacity
15 hours for 95% capacity

CAUTION

WHEN AN MBU IS INSTALLED IN THE MFS THE UPPER STORAGE TEMPERATURE IS 65°C INSTEAD OF THE USUAL 75°C.

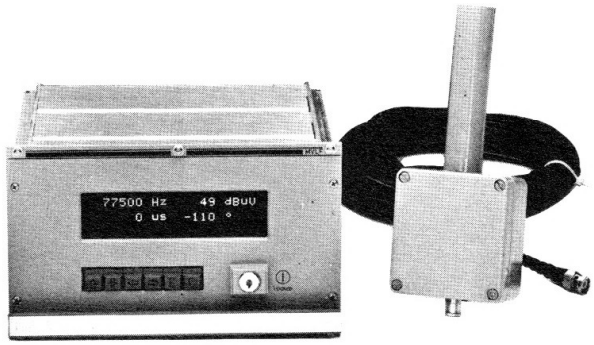
Low Voltage Cut Off When the batteries voltage drops below the required voltage to operate the system, the MPS automatically turns off the MFS. This prevents the batteries from going into a "deep charge" condition.

LED Indicators on Front Panel

On	(Grn)	Indicates MBU is discharging
Recharge Required	(Red)	ON if MBU requires charging
High Charge	(Amber)	ON if MBU is receiving full charge
Trickle Charge	(Grn)	ON if MBU is receiving trickle charge

BALL CORPORATION, EFRATOM DIVISION

Frequency Receiver and Clock Display – MVLF, VLF/LF Frequency and Time Receiver



The Modular Frequency Receiver, Model MVLF, receives signals from the standard time and frequency transmitters in the VLF and LF bands. It phase-locks the MRK Rubidium Frequency Standard to the received signal. An appropriate time constant is selected to retain excellent short-term stability and phase noise characteristics, while simultaneously eliminating the aging experienced by a stand-alone Rb oscillator. An active E-field antenna (mounted separately) is supplied with the MVLF.

The MVLF includes a clock with display, providing the user with time-of-day (hour, minute, second), date (year, month, day), day-of-year and modified Julian Date information. It features 1 PPS phase shifting capability in decade steps of 100 nanoseconds to 1 sec. Leap seconds may be inserted automatically at the proper time as announced by the BIH (Bureau Internationale de l'Heure). The user may program the event at any time by specifying year, month, day, hour and minute. The clock is manually set to the nearest second of UTC via whatever means available (i.e., telephone). The MVLF determines the delay of the received amplitude modulated 1 PPS available from OMA, MSF, WWVB, HBG or DCF77. Due to limited bandwidth of the transmitting antenna and the atmospheric background noise, the accuracy is limited to approximately one millisecond. If however, time can be transferred to the MVLF by any other more accurate means, it can be maintained to approximately 200 nsec by tracking the carrier phase of the received signal.

Model Number	Description
MVLF-OA1CO	11.8 - 77.5 kHz
MVLF-1A1CO	50.0 - 162 kHz

Electrical Specifications

Frequency Tuning Range

Omega-Hawaii	11800 Hz	MSF-Great Britain	60000 Hz
Omega-Liberia	12000 Hz	WWVB-USA	60000 Hz
Omega-Norway	12100 Hz	HBG-Switzerland	75000 Hz
Omega-Reunion	12300 Hz	DCF77-W. Germany	77500 Hz
Omega-Japan	12800 Hz		
Omega-Argentina	12900 Hz	**Optional Tuning Range**	
Omega-Australia	13000 Hz	Deutschlandfunk	153 kHz
Omega-N. Dakota	13100 Hz	France Inter. France	162 kHz
OMA-Czechoslovakia	50000 Hz		

Receiver Bandwidth (-3 dB) 200 Hz
(-60 db) 1.5 kHz

Receiver Sensitivity 1 microvolt

S/N Ratio Required for Phase Tracking -30 dBc/100 Hz BW

Phase Tracking Accuracy 0.01 cycles (typ)

Time Accuracy

Can maintain time transferred to the MVLF to within:

< 1 microsec. For VLF, 11.8 to 13.1 kHz
< 0.2 microsec. for LF, 50 to 77.5 kHz

Note: The above are typical values for distances up to 5000 km from the transmitter for VLF and 500 km for LF

Clock Functions

- Automatic leap year correction
- Automatic leap second correction at pre-programmed time up to 100 years in advance
- Synchronization to external 1 PPS (± 150 nanosec)
- Push button operated phase shifting in decade steps 100 nanosec. to 1 sec.
- Push button operated clock and calendar setting

Outputs

Display: Vacuum fluorescence, 40 ASCII character, in (2) lines; frequency, phase, field strength, last update, time of last update, time of day, date, day of year, modified Julian date.

1 PPS: 10 microsec. nom. pulse width
10 nsec max rise time
10 nsec max jitter
5 volts nominal into 50 ohms (adjustable 3 to 11 volts)

Control: 0 to 5 Vdc (14 bit DAC for MRK C-Field Control)

Recorder: Phase: 0 to 10 Vdc for ± 0.5 cycles
Field Strength: 0 to 10 Vdc for 0 to +100 dB microvolt

Inputs: 10 MHz from MRK Rb oscillator
0.5 to 1.5 Vrms into 50 ohms
1 PPS sync
50 nsec minimum pulse width
100 nsec. maximum rise time
3 to 11 volts into 50 ohms

Power: 20.5 Vdc, ~12W

CAUTION

WHEN AN MVLF/MRTC IS INSTALLED IN THE MFS, THE LOWER OPERATION TEMPERATURE IS 0°C INSTEAD OF THE USUAL -25°C.

MRTC Realtime Clock and IRIG Code Generator

When only the clock functions are desired, without the MVLF receiver, an MRTC can be requested. This unit is housed in the same configuration as the MVLF. Therefore, the environmental and physical characteristics described earlier apply to the MRTC. The power requirements for the MRTC are fulfilled by the MPS (20.5 Vdc), approx. 12 watts.

Model Number	Description
MRTC-OA1CO	No IRIG Output
MRTC-1A1CO	IRIG Outputs

IRIG Code Generator (option for MRTC only)

4 standard IRIG formats are programmable from front panel buttons.

Electrical Specifications

Rate Designation
A) 1000 pps
B) 100 pps
E) 10 pps
G) 10000 pps

Form Designation Modulated
1) Sine Wave, Amplitude

Carrier Frequency / Resolution
1) 100 Hz / 10 ms
2) 1 kHz / 1 ms
3) 10 kHz / 0.1 ms
4) 100 kHz / 0.01 ms

Coded Expressions
2) BCD
3) BCD. SBS

Open Loop Output Level Adjustable, 0 ... > 2 Vrms

Source Impedance 600 ohms

Modulation Adjustable, 0 ... 100%

Rate Epoch Error* < 200 nsec

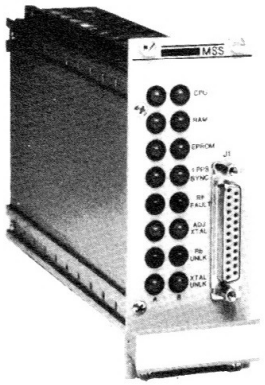
Carrier Epoch Error* < 5% of resolution
*referred to MRTC 1 PPS output

Rate, Carrier, Code Selection Via MRTC Display menu

Software requirement Version 0300 or higher

System Status

MSS, System Status



The Modular System Status, Model MSS, provides monitoring of CMOS / TTL compatible signal from a Modular Frequency System (MFS). If two sub-systems reside in the same MFS enclosure (typically, each sub-system contains a MPS, MRK, and MBF module as a minimum) half of the status module is dedicated to one sub-system while the other half of the status module is dedicated to the other sub-system. Panel mounted LED's provide visual parameter status and a front panel mounted connector provides remote status monitoring capability. This remote status connector provides CMOS / TTL compatible output status signals for all signals being monitored. The module also contains dual relays (one per sub-system) for relay closure type monitoring. Up to eight signals can be monitored by each relay and normally open or normally closed fault indication may be specified. The module also provides for one pulsed status input signal (the presence of a repetitive pulse means the parameter monitored is okay) for each sub-system. The signals to be monitored must be specified at the system level and are hard-wired in the mainframe. The front panel LED's and labeling are dependent on signals chosen for monitoring.

MSS Model	Description
MSS-OAOCO	Standard Status Module

Electrical Specifications

Inputs Up to six (twelve) individually statused CMOS / TTL compatible signals per sub-system (system). Up to eight (sixteen) group statused CMOS / TTL compatible signals per sub-system (system). One (two) pulsed CMOS / TTL compatible signal(s) per sub-system (system).

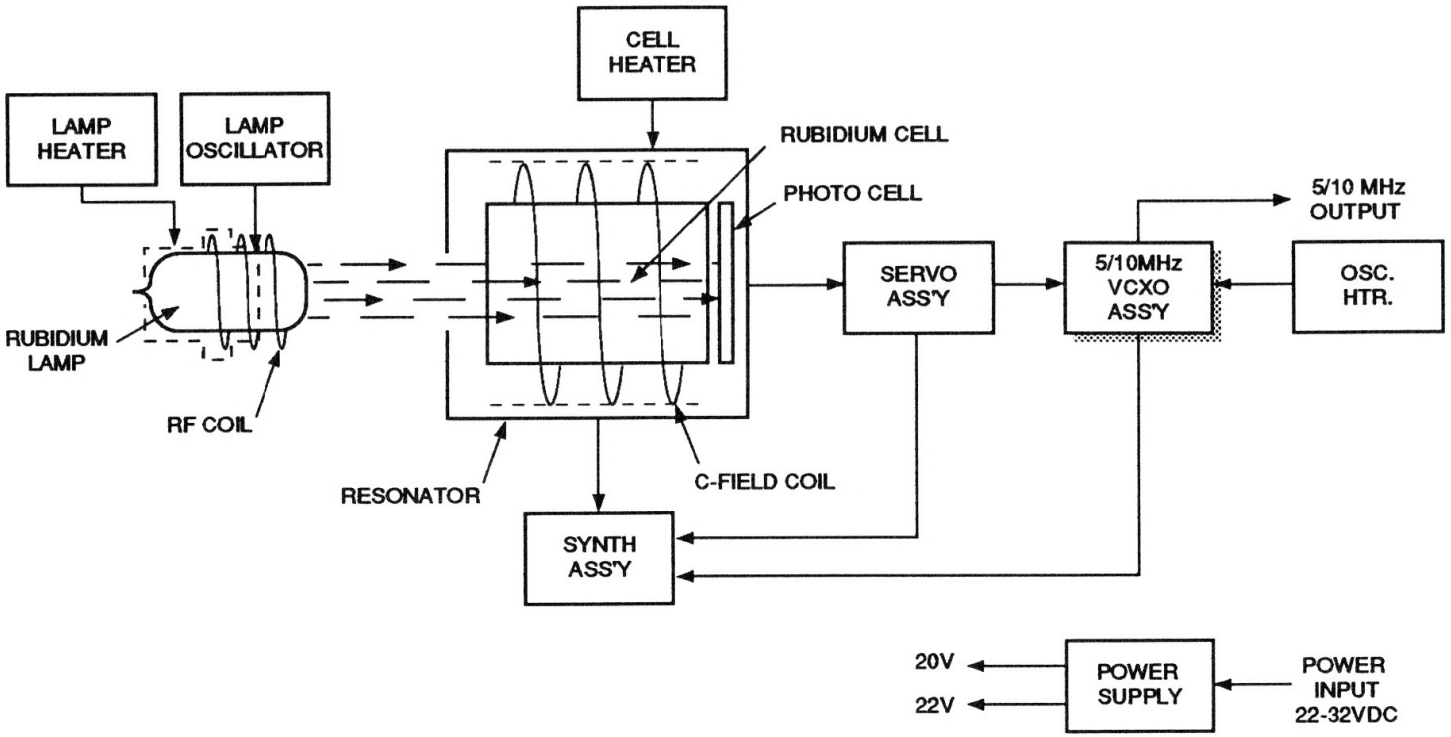
Outputs Eight (sixteen) CMOS/TTL compatible signals per sub-system (system) on status port. One (two) relay closure(s) per sub-system (system) on status port. Eight (sixteen) LED status indicators per sub-system (system).

Input Power 20.5 Vdc, 4.0 W (system)

PERFORMANCE SUMMARY

THE FOUR BASIC RUBIDIUM OSCILLATOR MODELS COMPARED

Ball Efratom Division



THE FOUR BASIC RUBIDIUM OSCILLATOR MODELS COMPARED (continued)

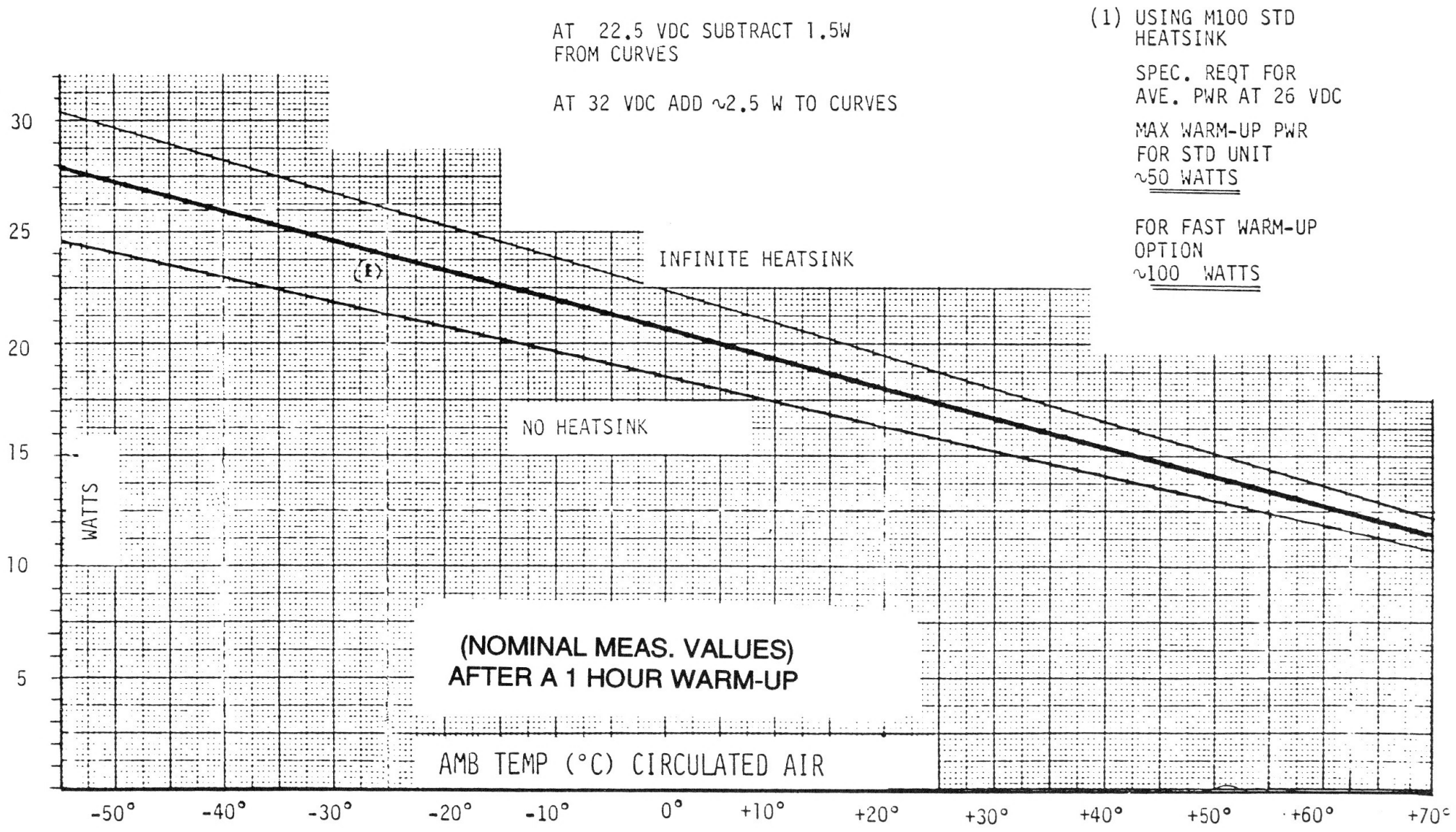
Ball Efratom Division

DESCRIPTION	MIL M100	COM'L FRK	MIL M3000	COM'L FRS
WARM-UP (IN MINUTES)	~10	~10	~4.0 @-55°C	~4 (LOCK)
POWER	~18W	~13W	~16W	~10W
OPS. TEMP	-55/+68°C*	-55/+65°C*	-55/+80°C*	-55/65°C*
STOR'G TEMP.	-62/+85°C	-55/+75°C	-62/+95°C	-55/+85°C
SHORT TERM STAB.	$\sigma\gamma(\tau) = 3E\text{-}11\ (\tau^{-1/2});\ 1s < \tau < 100s$			5E-11
AGING/MO.	6E-11	4E-4	6E-11	5E-11
	(1E-11 OPTIONAL)			
VOLUME	80 $in.^3$	67$in.^3$	48$in.^3$	24$in.^3$
WEIGHT	~4 lbs	~2.9 lbs	~2.5 lbs	~1.2 lbs
OSC. CRYSTAL	AT&SC-MIL	AT&SC-COM'L	SC-MIL	AT-COM'L
PARTS	MIL QPL	COM'L	MIL QPL	COM'L
RADIATION HARD. DESIGN	YES +TEST	N/A	YES +TEST	N/A

* BASEPLATE TEMP

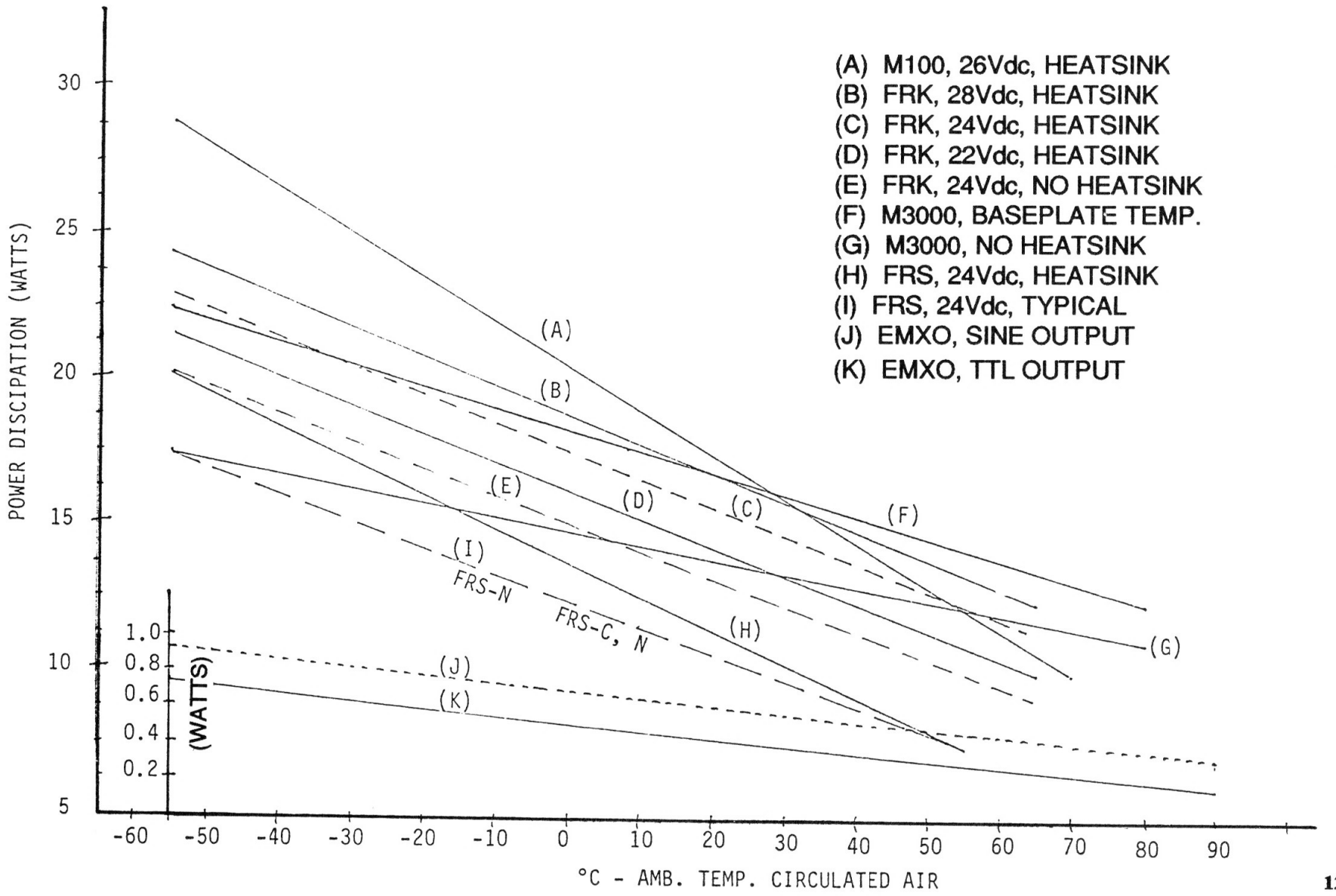
M100 POWER CONSUMPTION vs. TEMPERATURE (DETAILS)

Ball Efratom Division



FRS, FRK, M100, M3000, EMXO
POWER CONSUMPTION vs. TEMPERATURE

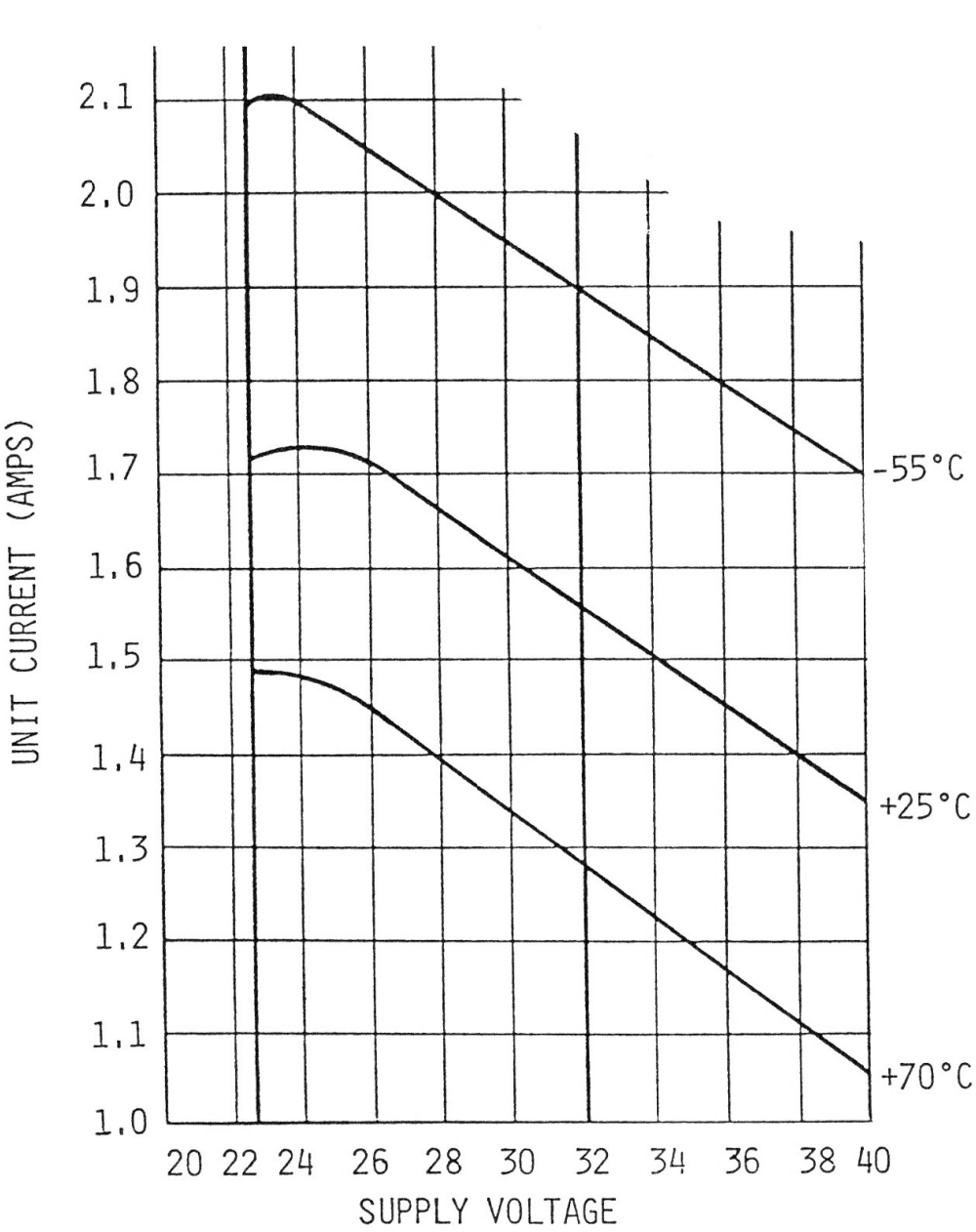
Ball Efratom Division

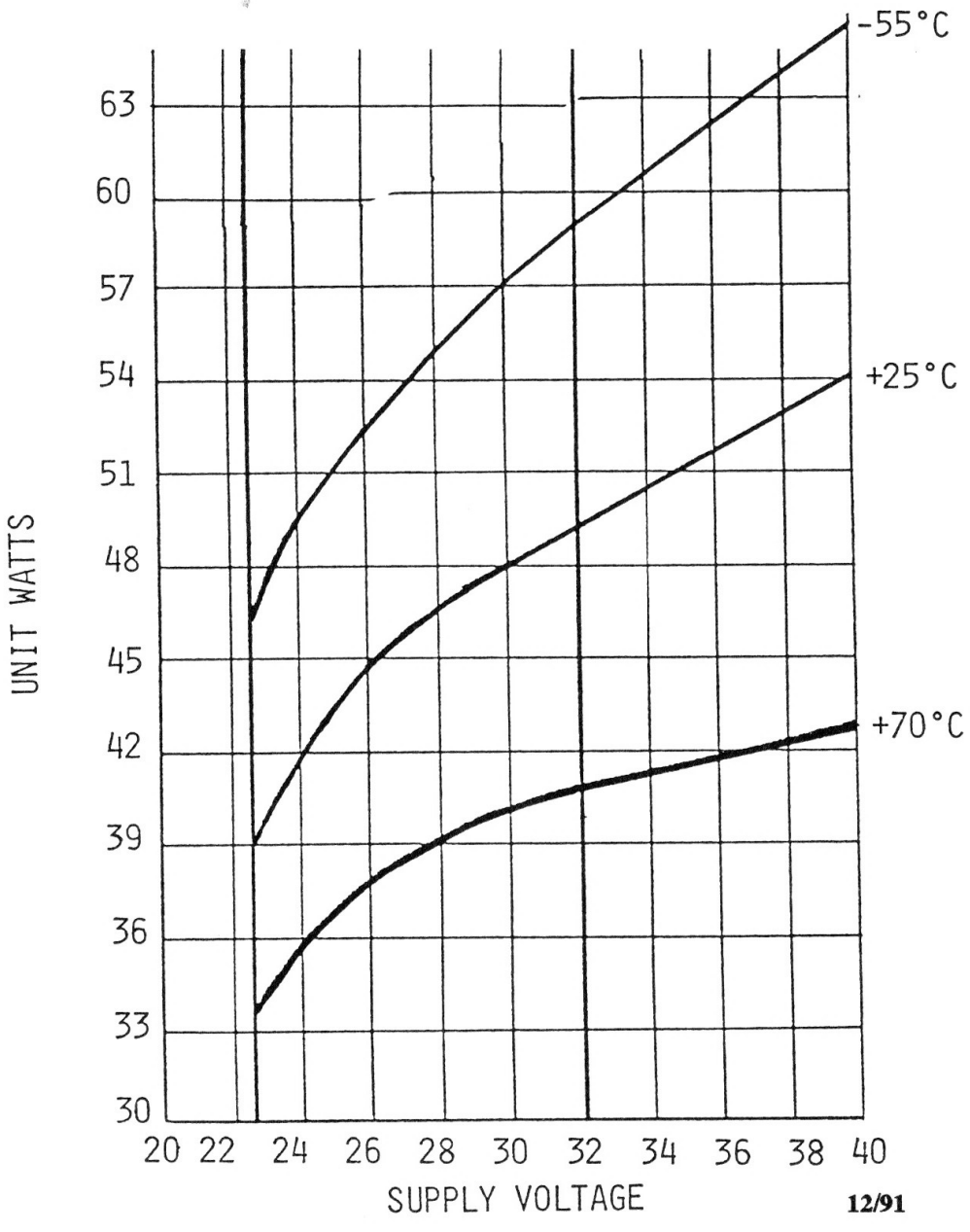


12/91

M100 CURRENT vs. SUPPLY VOLTAGE

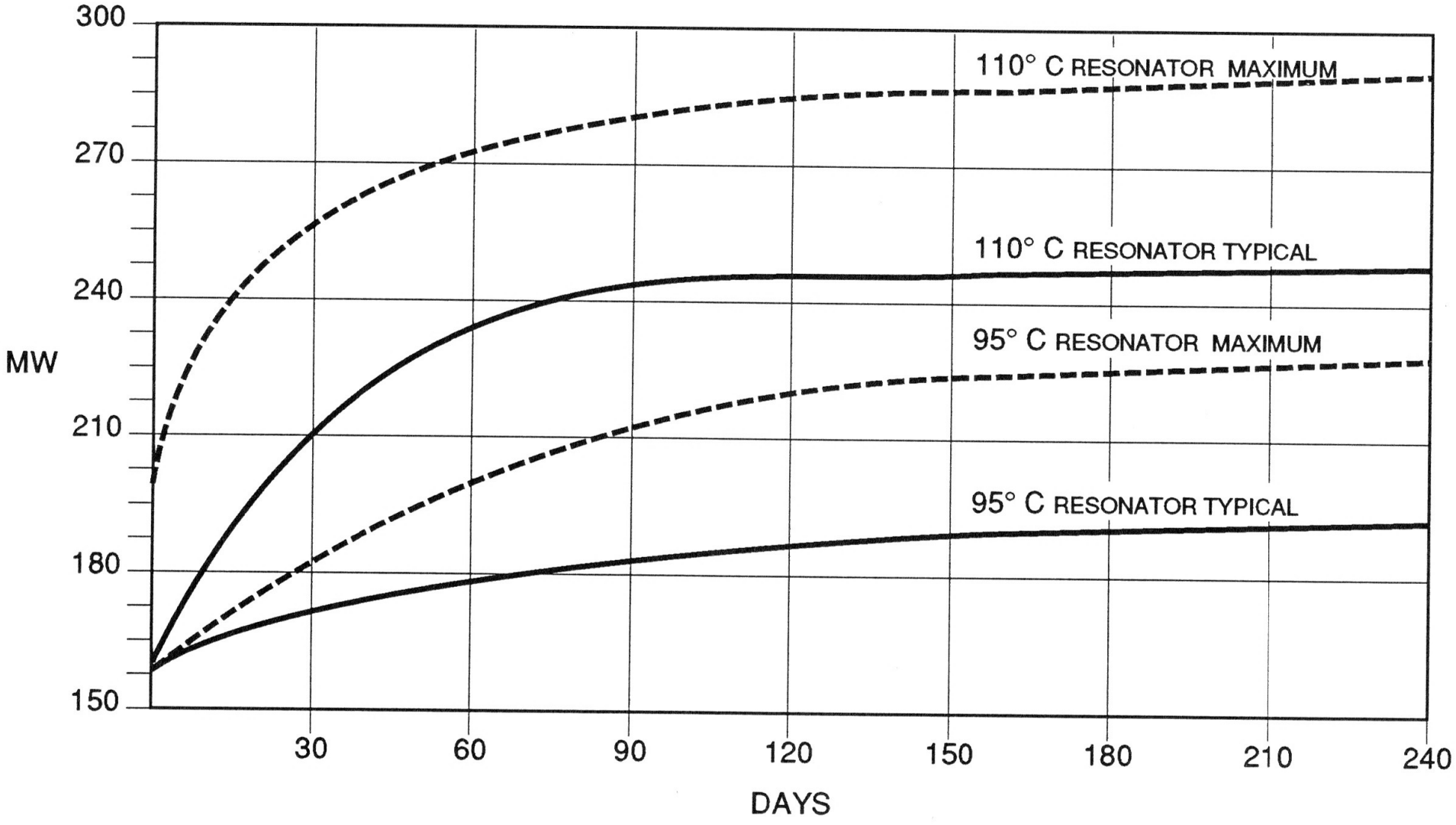
Ball Efratom Division





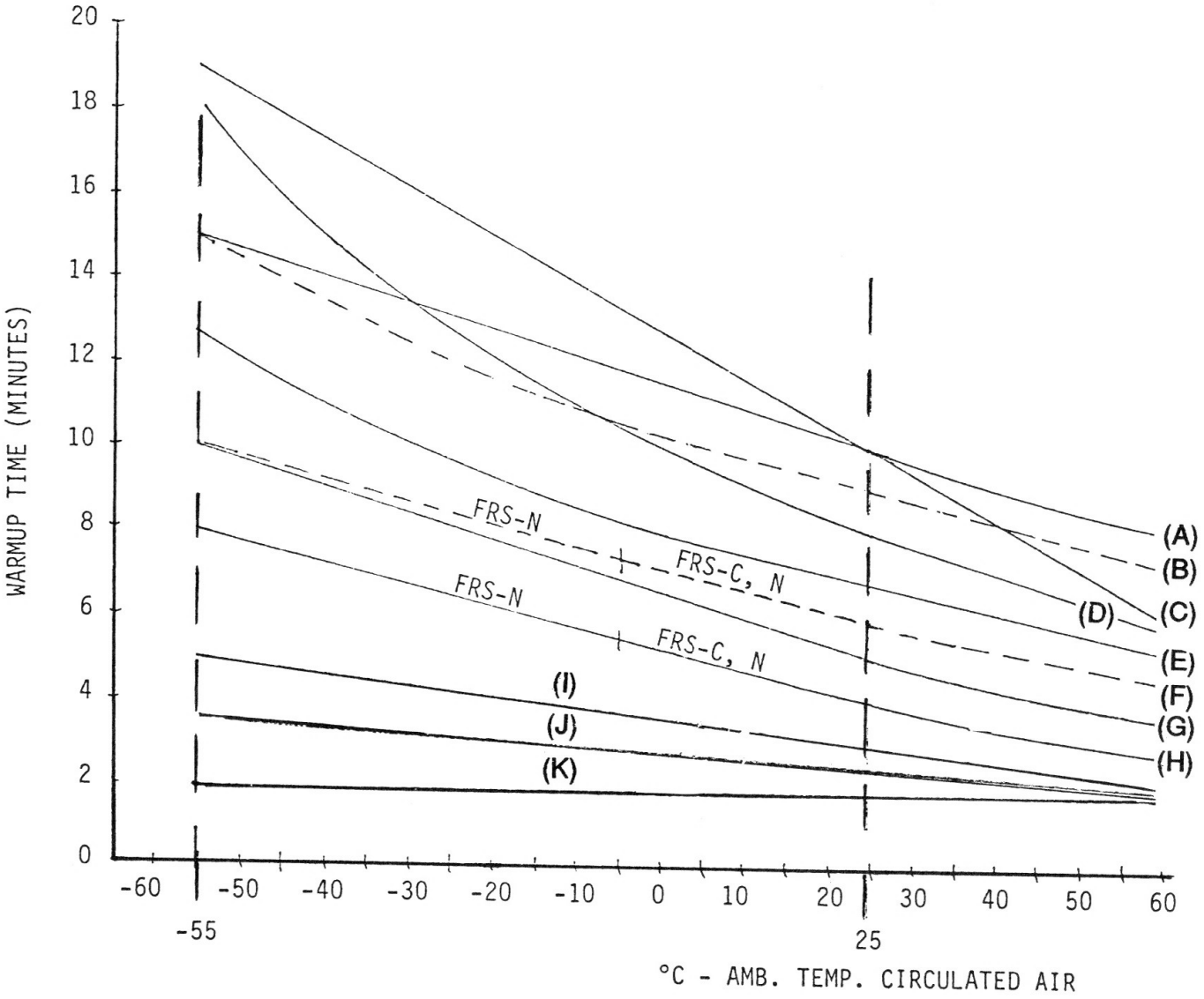
EMXO, ECXO POWER CONSUMPTION AGING

Ball Efratom Division



FRK, M100, FRS, M3000, EMXO WARM-UP TIME vs. TEMPERATURE

Ball Efratom Division

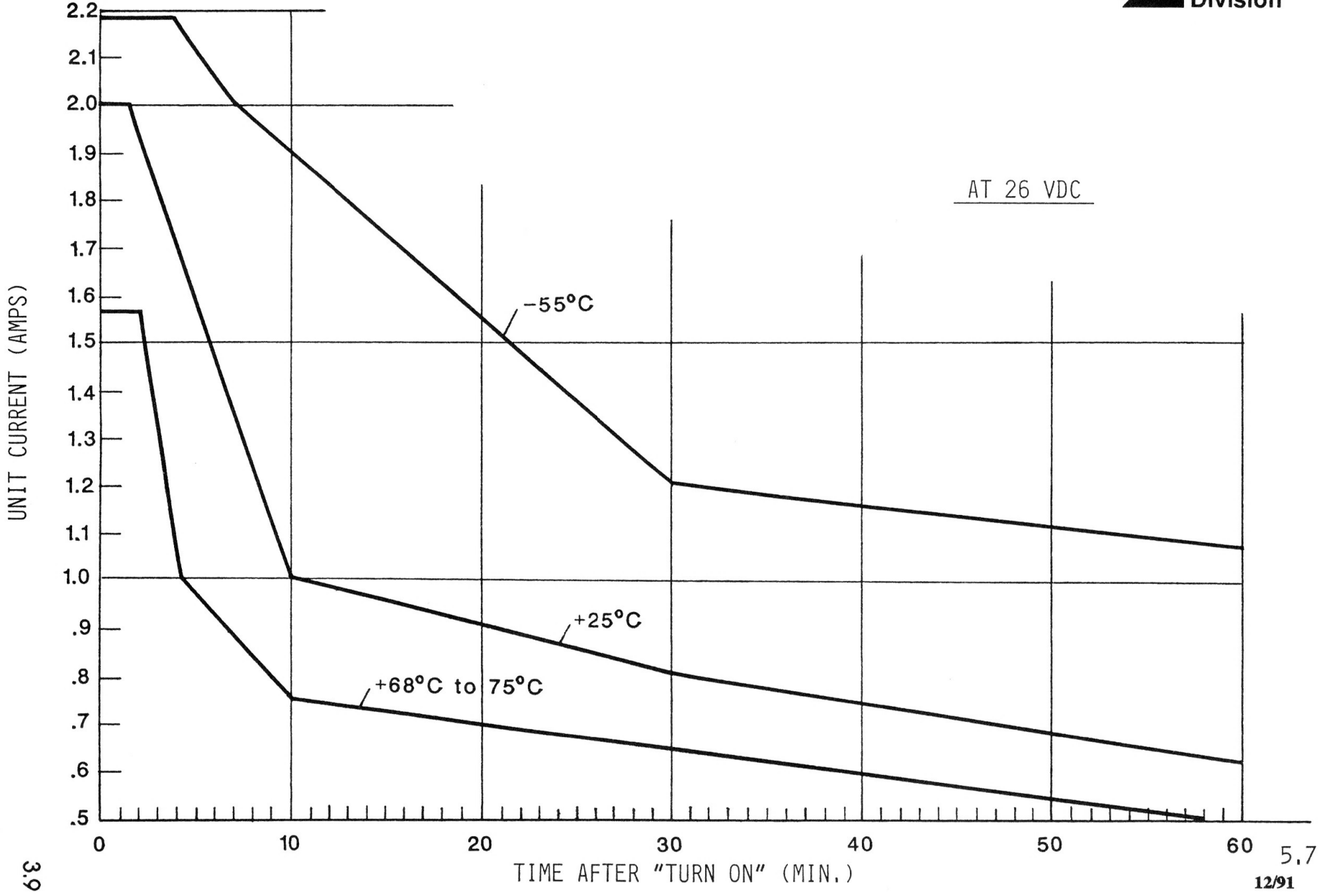


NOTES:
WITH STANDARD HEATSINK ATTACHED

(A) M100 (FOR 2E-10)
(B) M100 TYPICAL (FOR 2E-10)
(C) FRK (FOR 2E-10)
(D) FRK TYPICAL (FOR 2E-10)
(E) M100, FRK, TYPICAL (FOR 1E-9)
(F) FRS (FOR 1E-9)
(G) M100 FAST WARMUP UNIT (FOR 2E-10) AND M3000 (FOR 5E-10)
(H) FRS (FOR LOCK)
(I) M3000 (FOR 2E-9)
(J) M3000 (FOR LOCK) EMXO (FOR 1E-8)
(K) EMXO (FOR 1E-7)

M100 WARM-UP CURRENT vs. TIME

Ball Efratom Division



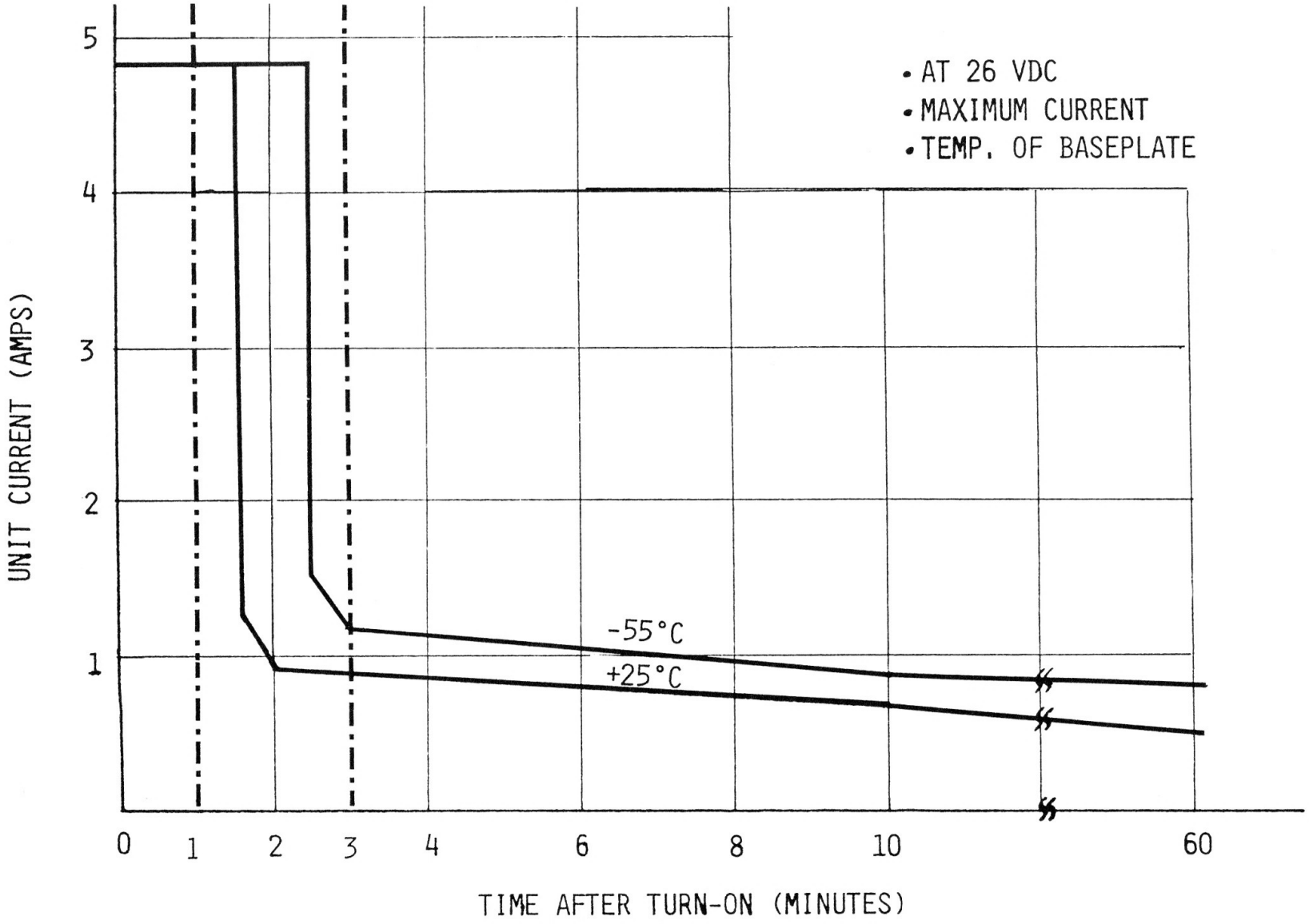
3.9

5.7

12/91

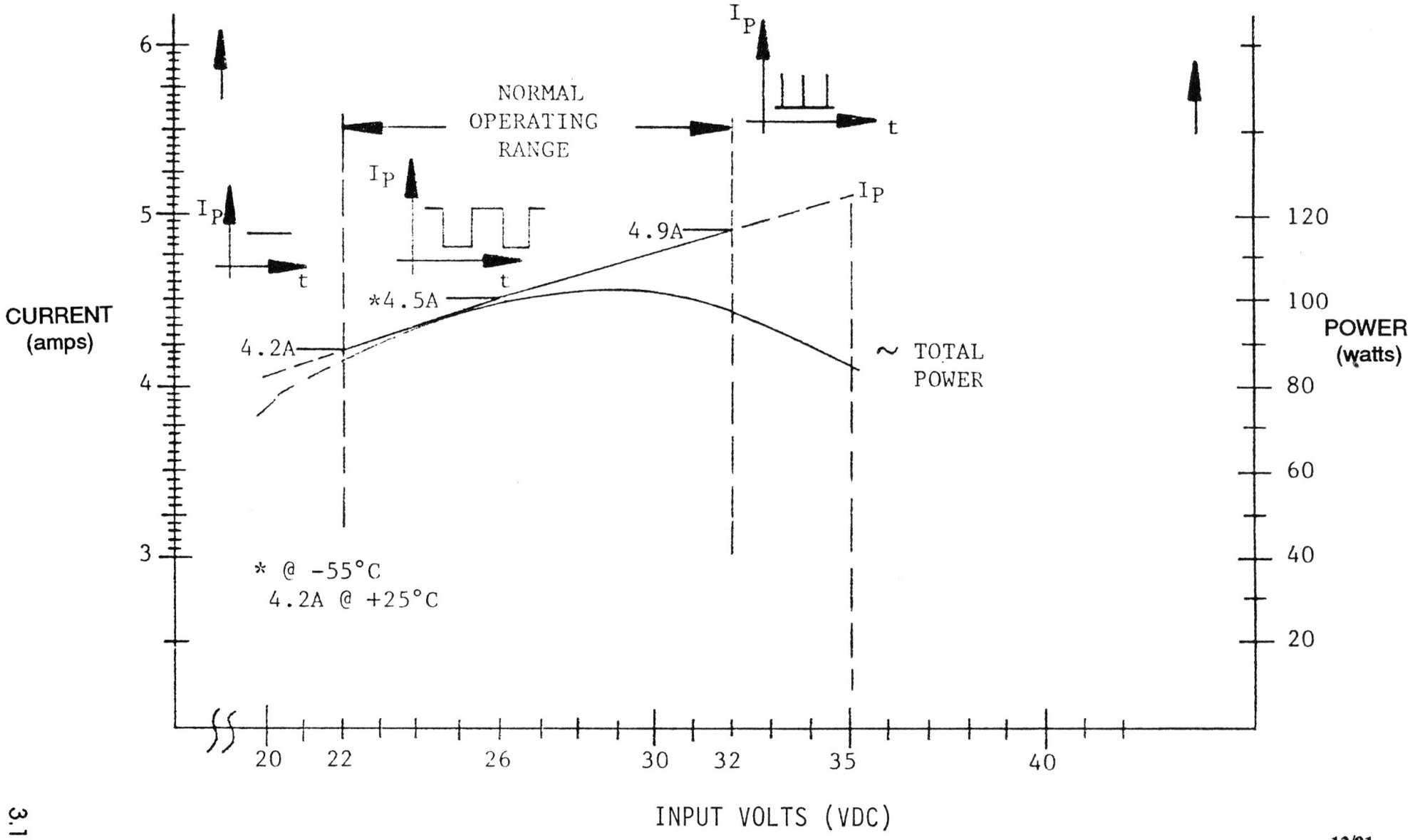
M3000 WARM-UP CURRENT vs. TIME

Ball Efratom Division



M3000 WARM-UP CURRENT vs. INPUT VOLTAGE

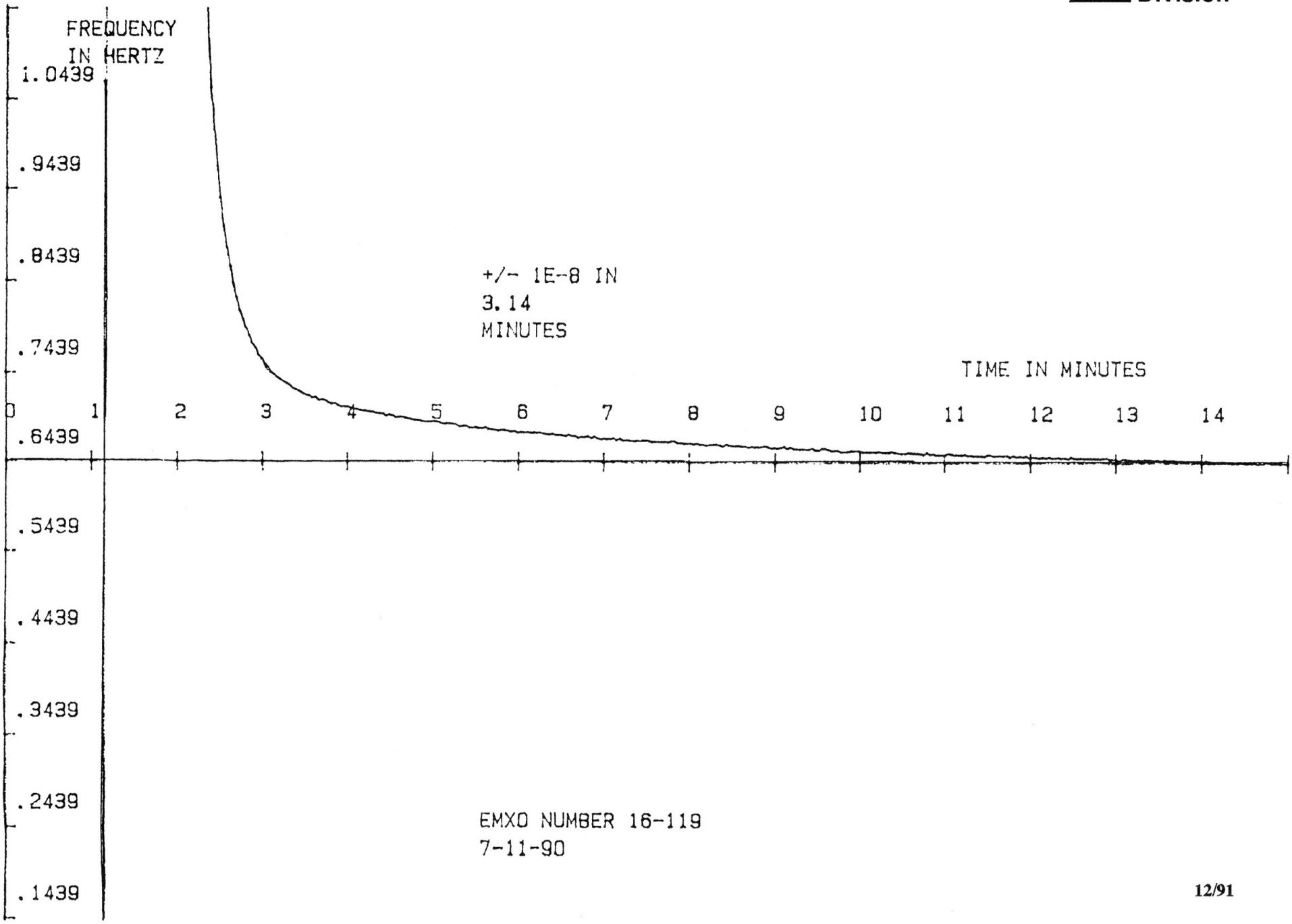
Ball Efratom Division



12/91

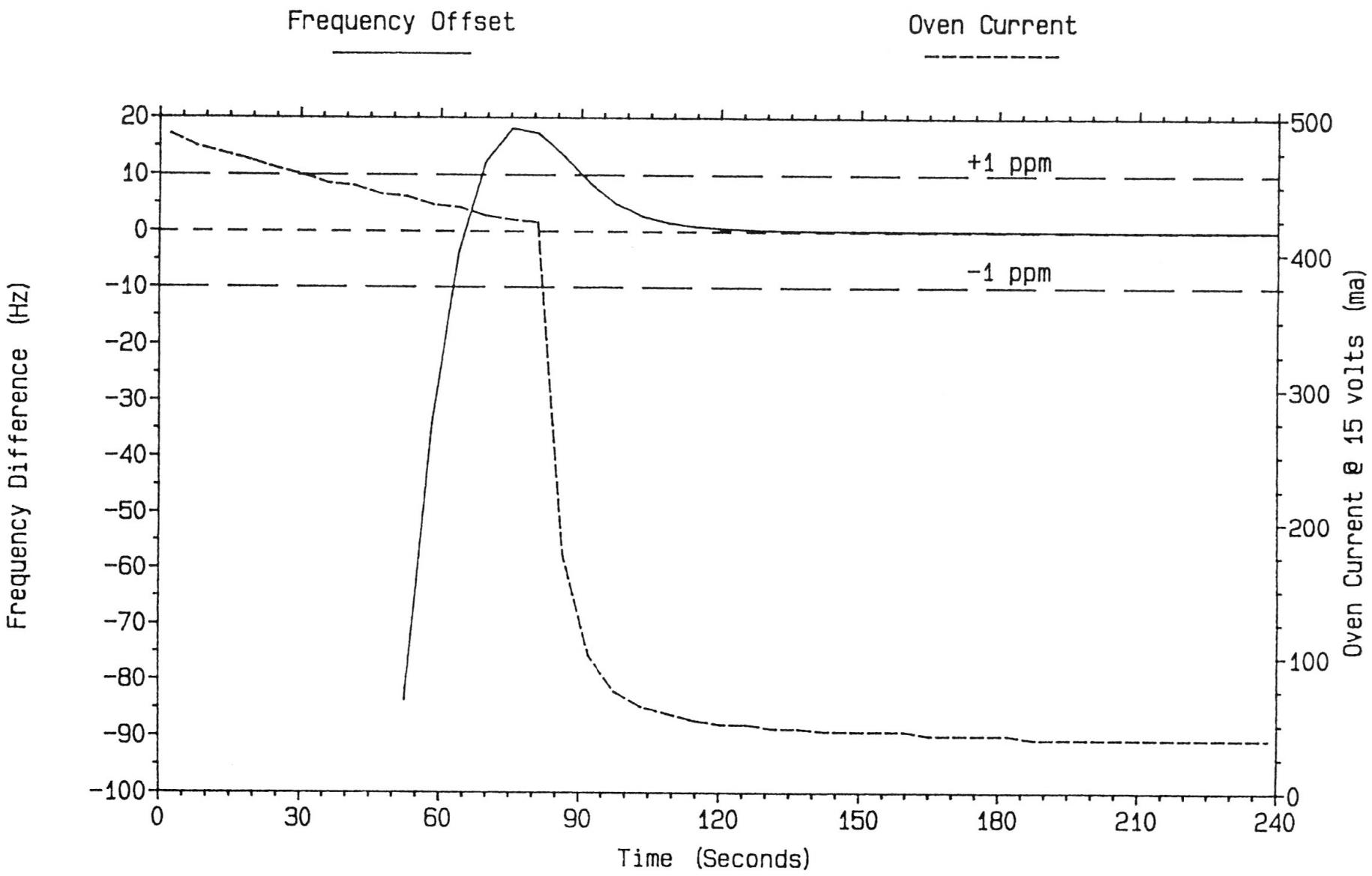
EMXO WARM-UP TIME AT -55°C, MEASURED DATA

Ball Efratom Division



EMXO WARM-UP TIME vs. OVEN CURRENT AT -55°C

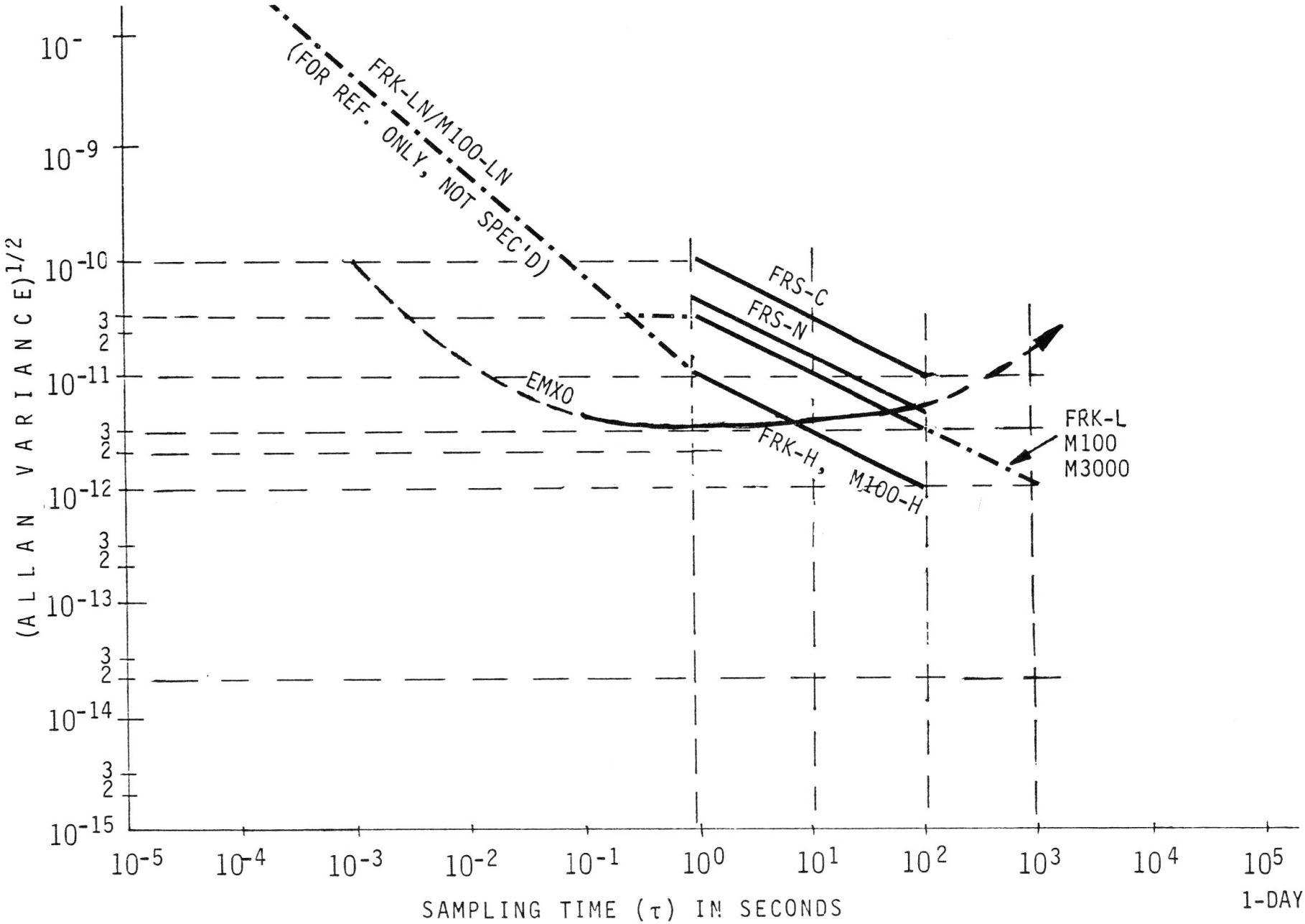
Efratom Division



12/91

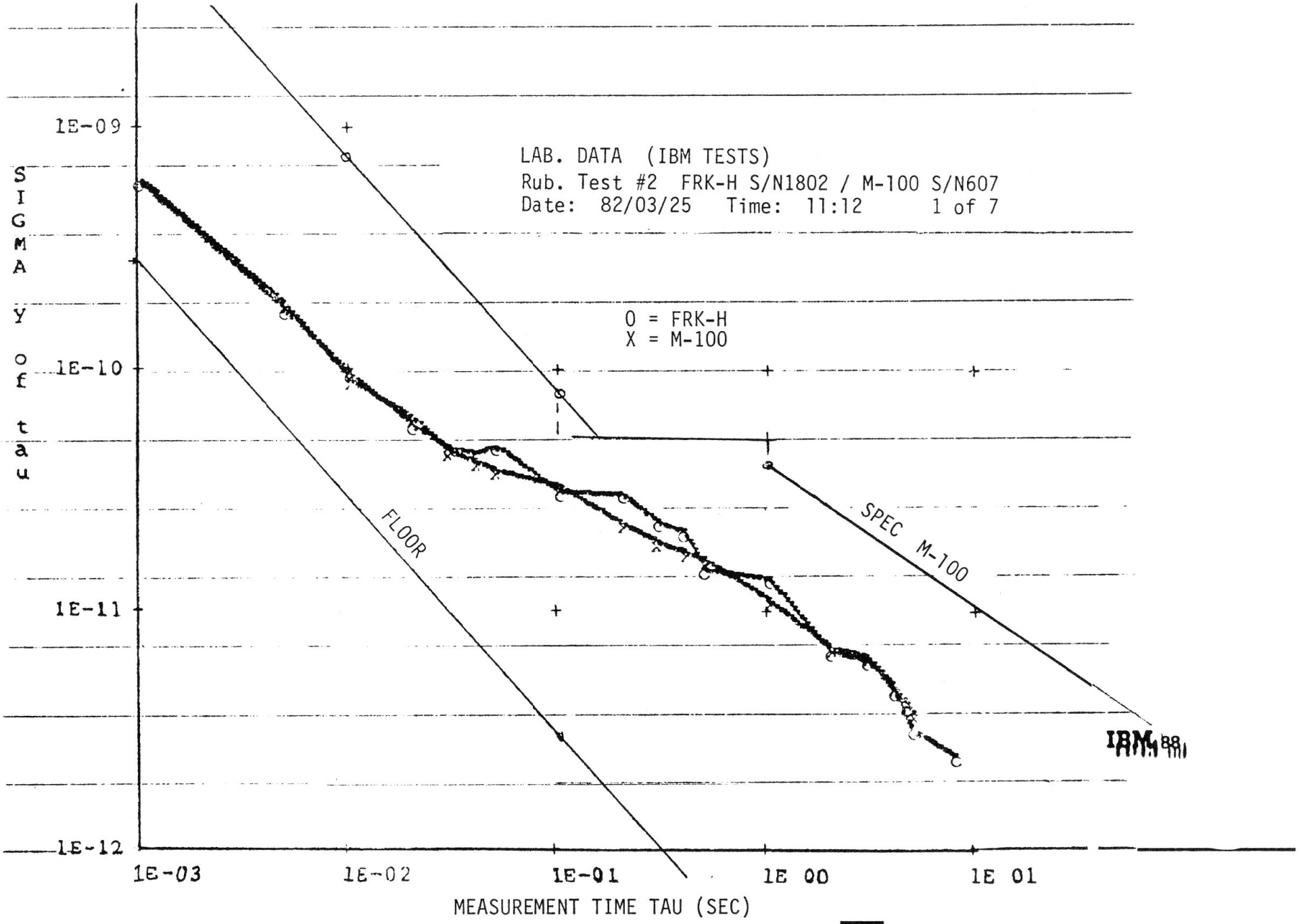
FRS, FRK, M100, M3000, EMXO SHORT-TERM STABILITY

Ball Efratom Division



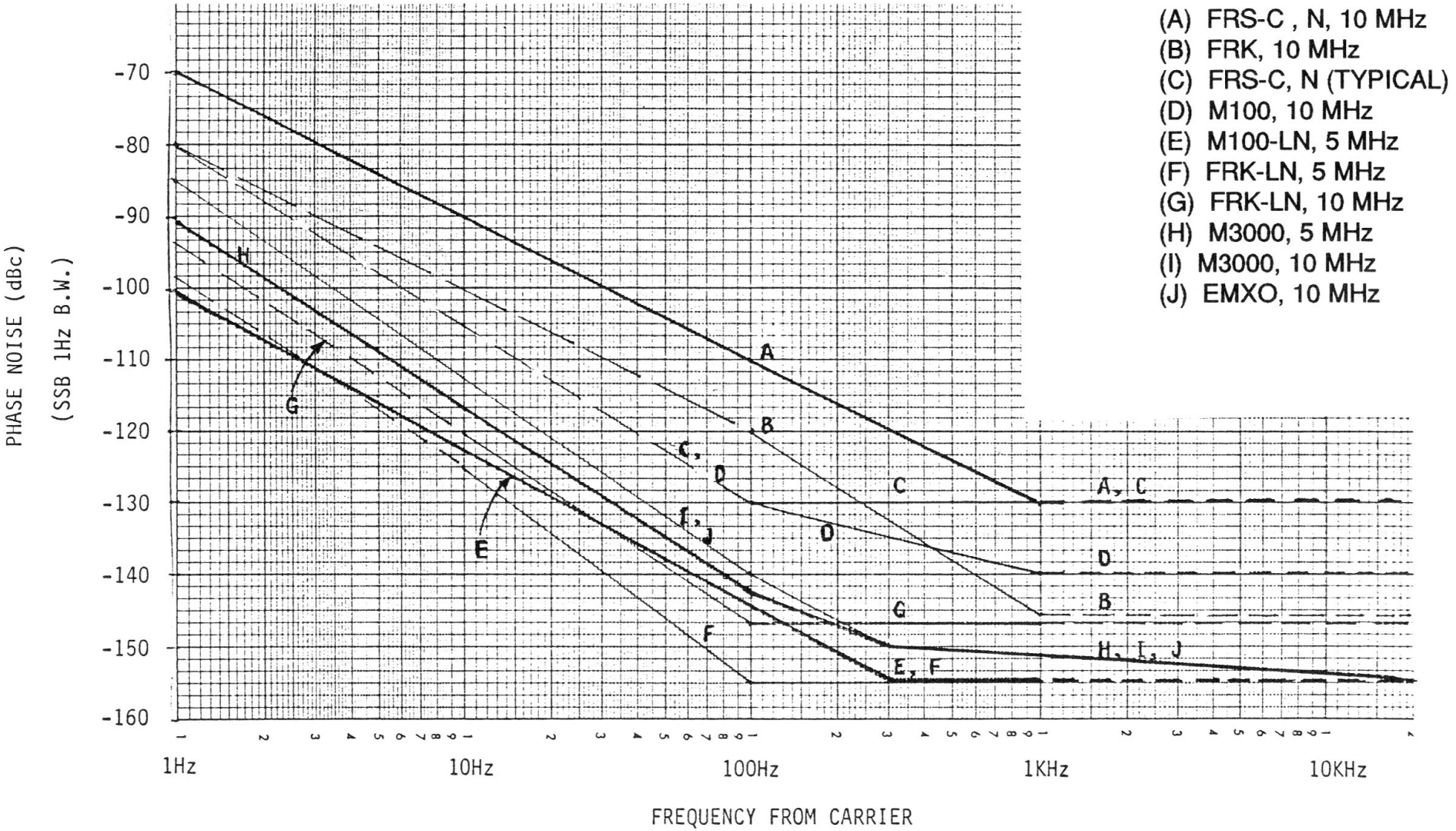
M100, FRK SHORT-TERM STABILITY, MEASURED DATA

Ball Efratom Division



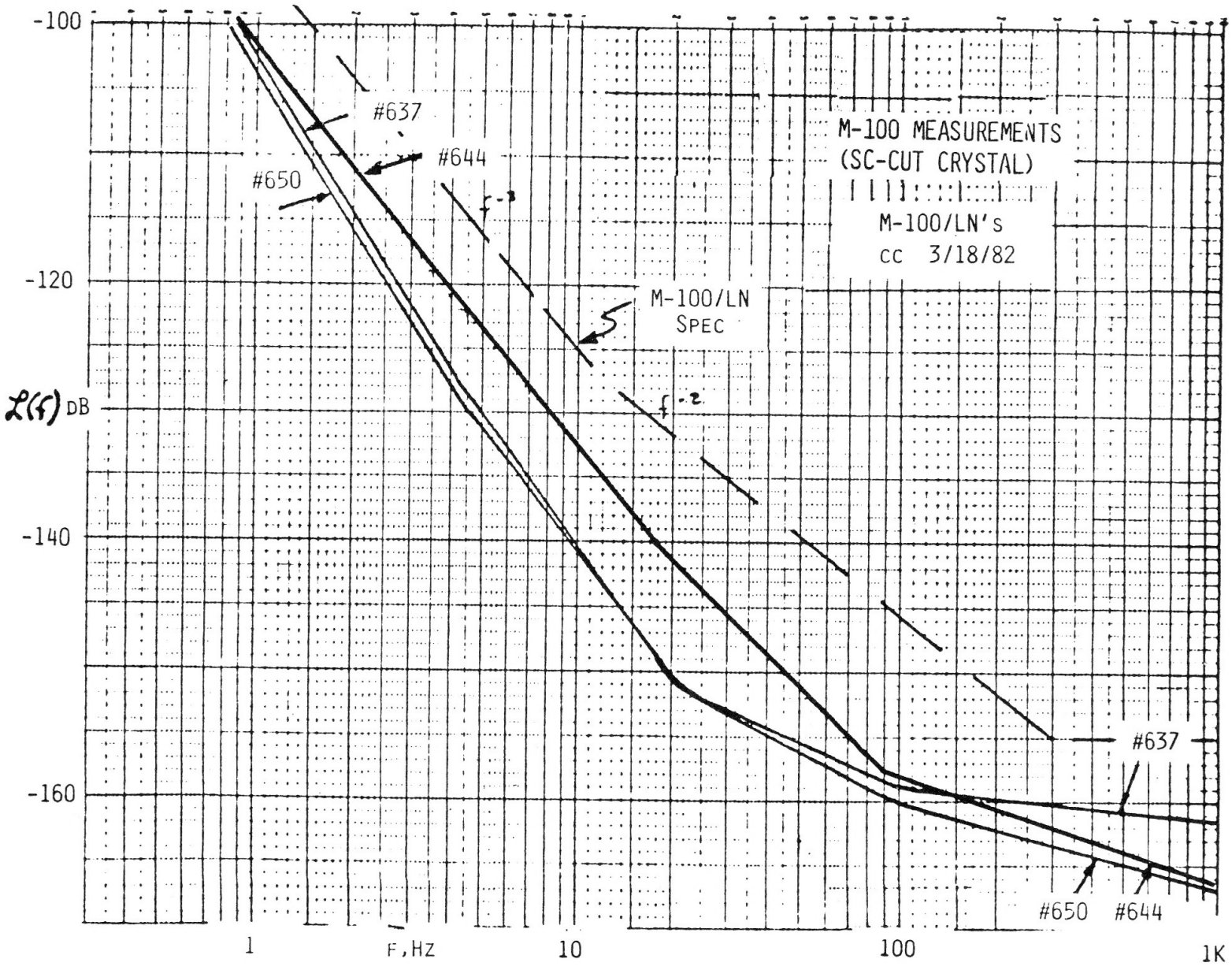
FRS, FRK, M100, M3000, EMXO PHASE NOISE

Efratom Division



M100-LN PHASE NOISE, MEASURED DATA

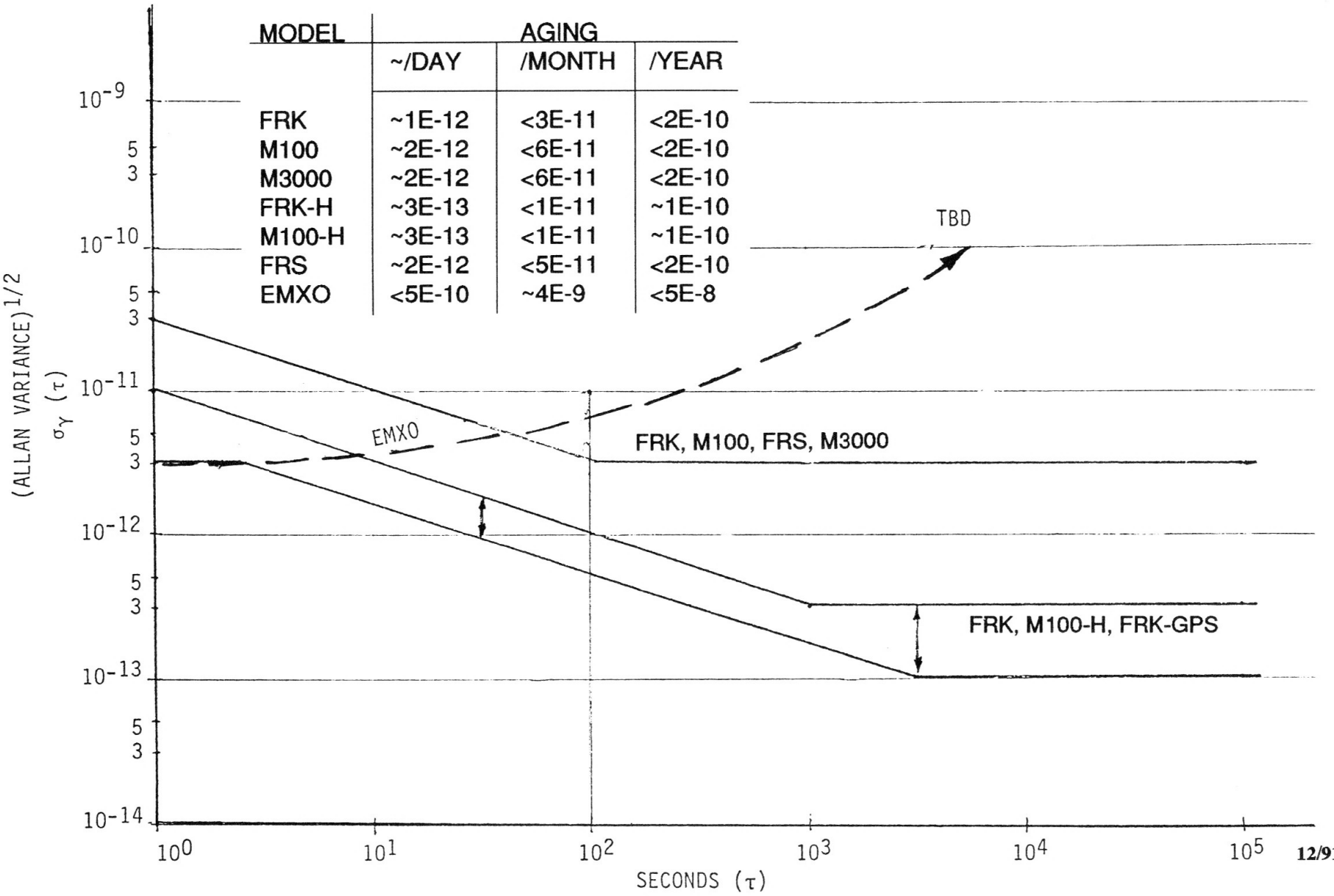
Ball Efratom Division



FRK, M100, FRS, M3000, FRK-GPS, EMXO
LONG-TERM STABILITY AND AGING

Ball Efratom Division

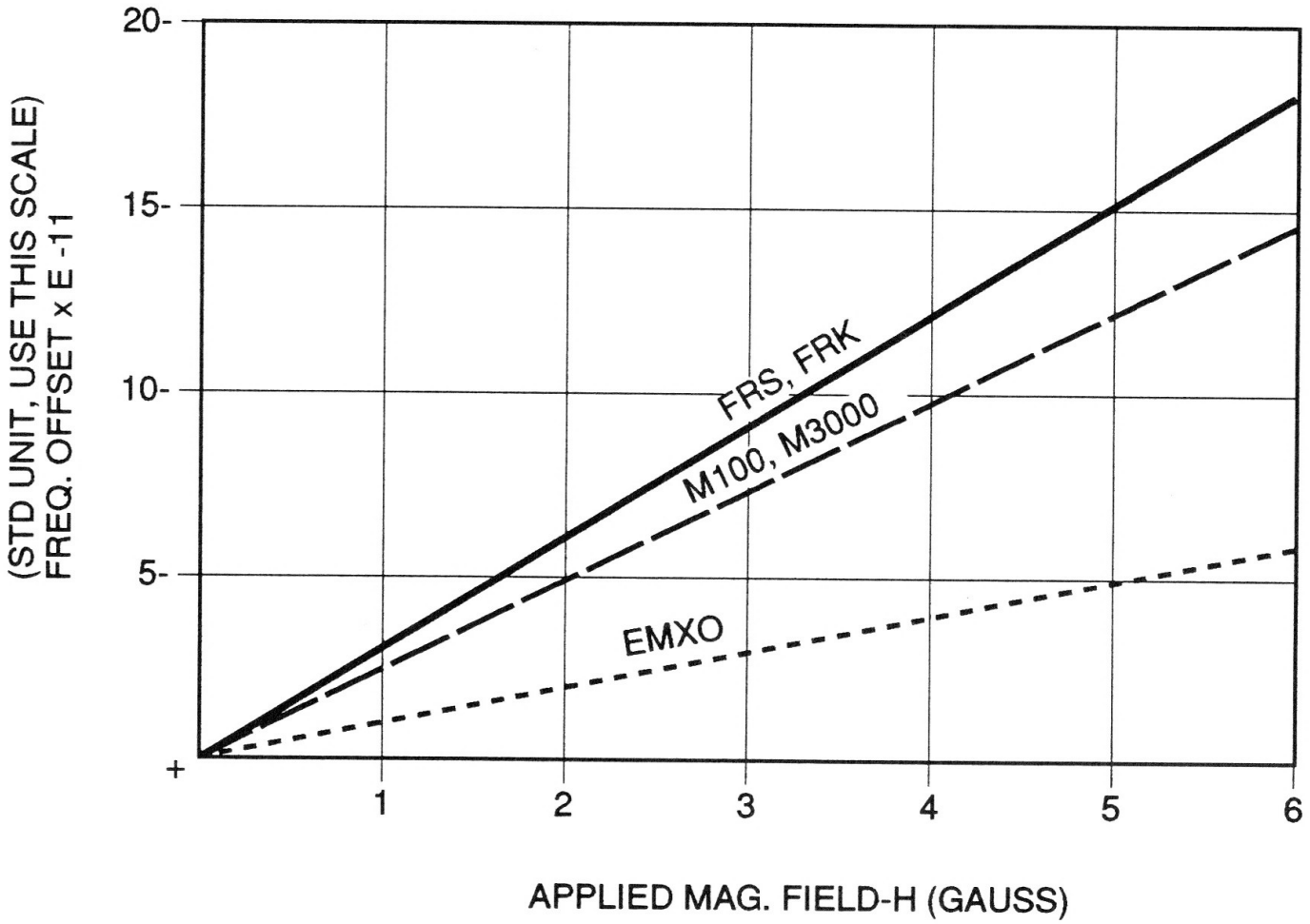
MODEL	AGING		
	~/DAY	/MONTH	/YEAR
FRK	~1E-12	<3E-11	<2E-10
M100	~2E-12	<6E-11	<2E-10
M3000	~2E-12	<6E-11	<2E-10
FRK-H	~3E-13	<1E-11	~1E-10
M100-H	~3E-13	<1E-11	~1E-10
FRS	~2E-12	<5E-11	<2E-10
EMXO	<5E-10	~4E-9	<5E-8



12/91

FRS, FRK, M100, M3000, EMXO MAGNETIC FIELD PERFORMANCE

Ball Efratom Division



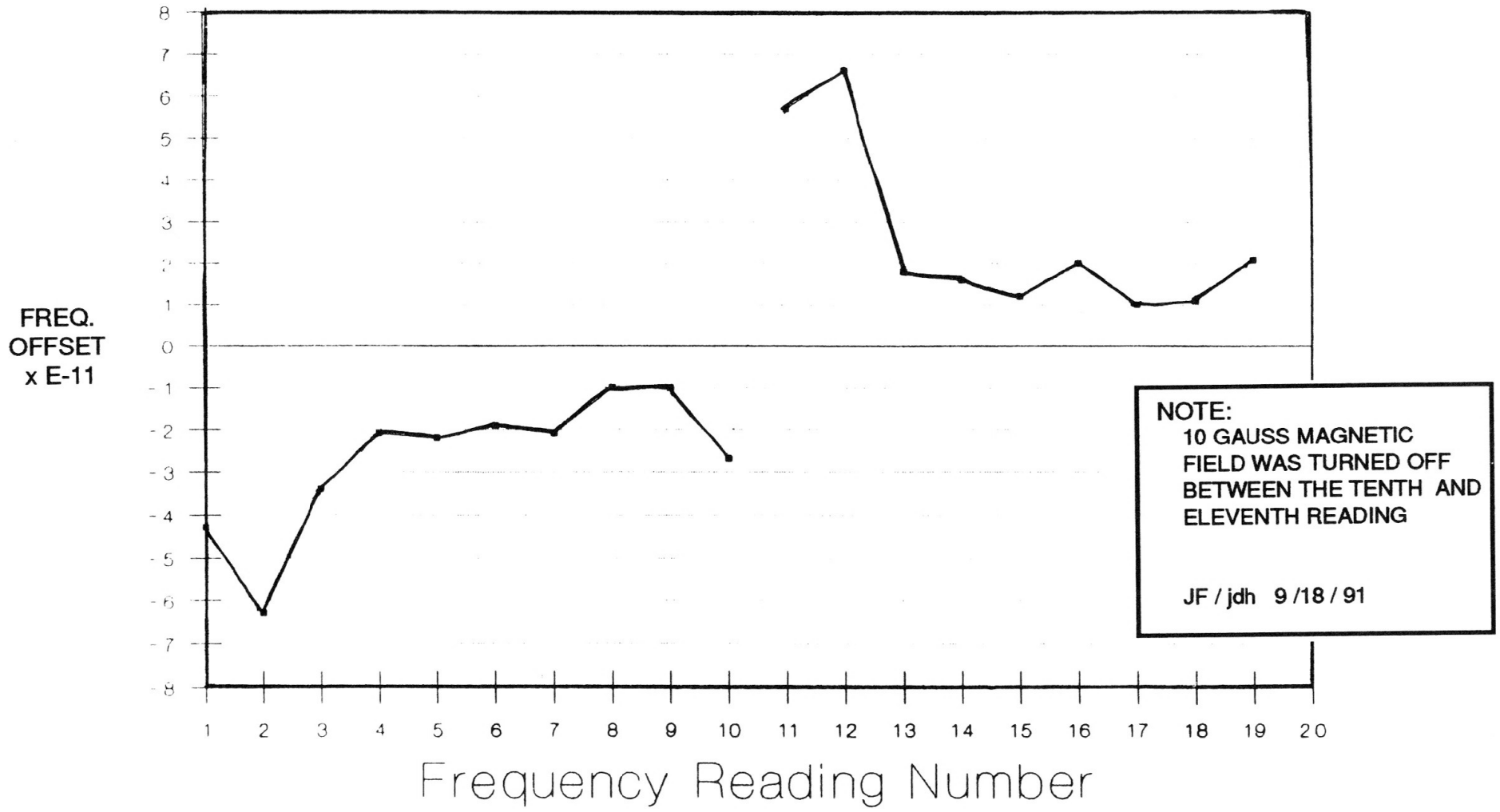
FREQ. OFFSET
x E-12

(PERFORMANCE WITH OPTIONAL MU-METAL SHIELD; USE THIS SCALE FOR FRK ONLY)

NOTE:
AM = AMPS / METER
1 GAUSS = 79.57 $\frac{A}{M}$
4 E -13 / AM $^{-1}$ = 3 E -11 (GAUSS)

EMXO MAGNETIC FIELD PERFORMANCE, MEASURED DATA, 10 GAUSS

Ball Efratom Division



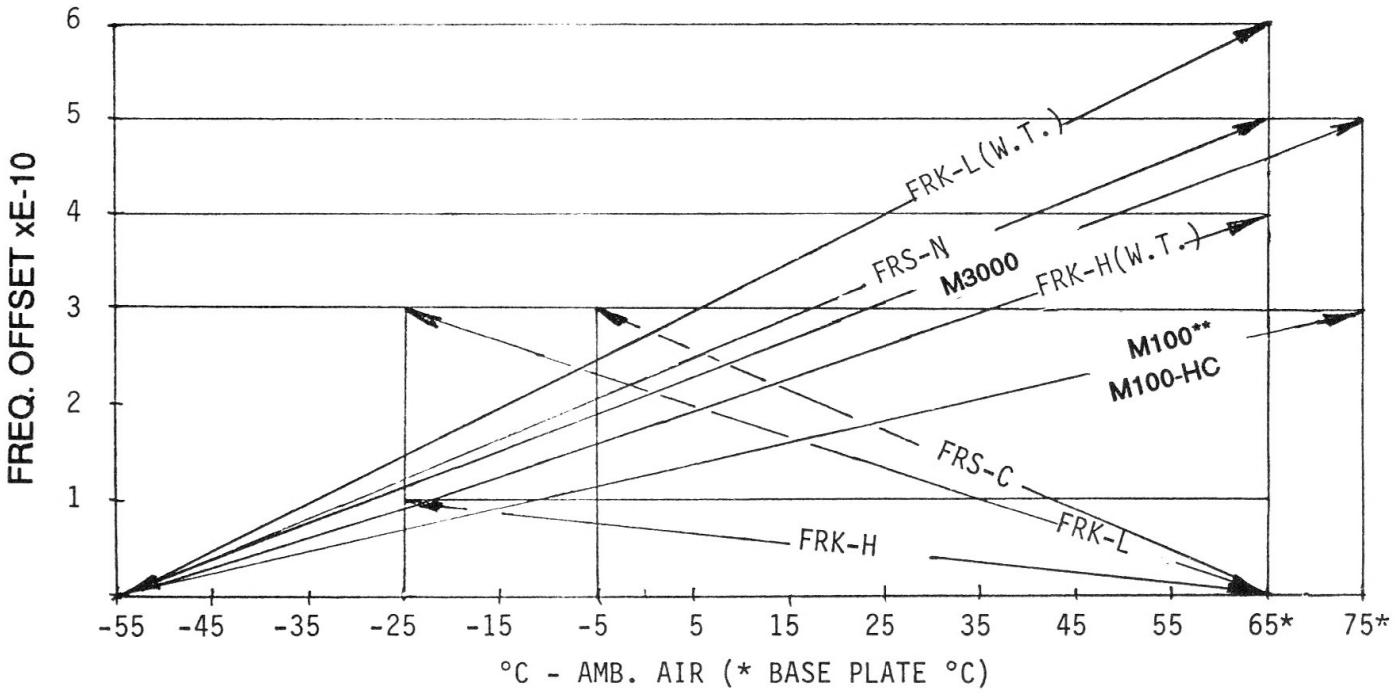
FRS, FRK, M100, M3000 TEMPERATURE COEFFICIENT

Ball Efratom Divisior

M100 STANDARD UNIT
FRK-L STANDARD UNIT
FRK-L (W.T.)-WIDE TEMP RANGE OPTION
FRK-H LOW AGING OPTION
FRK-H (W.T.)-WIDE TEMP RANGE OPTION
M100-HC (HIGHER TEMP OPTION)

T_c IS SPECIFIED AS A BOX, NOT A LINEAR FUNCTION WITH TEMPERATURE. FOR EXAMPLE:

FRS-N IS 5E-10 ANYWHERE WITHIN A BOX FROM -55°C TO +65°C B.P.



TEMPERATURE COEFFICIENT (T_c) OF THE FREQUENCY STANDARD IS THE SUM OF THE T_c OF THE PHYSICS PACKAGE AND THE T_c OF THE ELECTRONICS

THE T_c OF THE PHYSICS PACKAGE IS MONOTONIC. IT IS CAUSED BY THE FINITE GAIN OF THE THERMAL CONTROL CIRCUITS AND THE THERMAL GRADIENT OVER THE HEATERS.

THE T_c OF THE ELECTRONICS (e.g., MULTIPLIER AND SERVO ASSEMBLY) ARE NOT NECESSARILY MONOTONIC. **FOR THIS REASON WE SPECIFY THE T_c AS A BOX,** OUTLINING THE MAXIMUM STEADY STATE DEVIATION AT ANY TEMP.

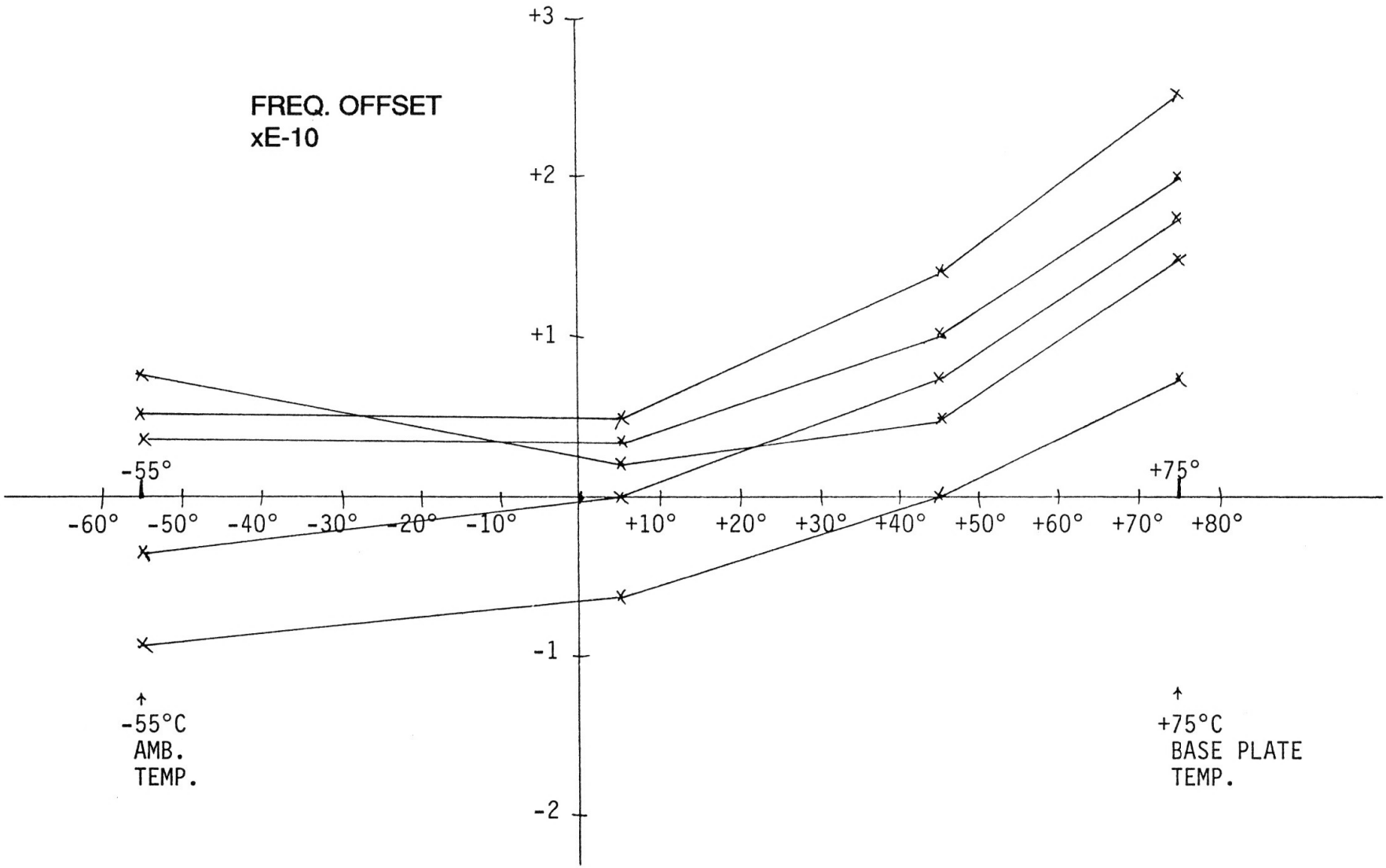
UNITS CAN BE HAND SELECTED AND ADJUSTED FOR A PARTICULAR BAND AND POLARITY OF COEFFICIENT BUT WOULD BE NON-STANDARD UNITS.

* BASE PLATE TEMPERATURE
** M100 TO 68°C BASEPLATE

12/91

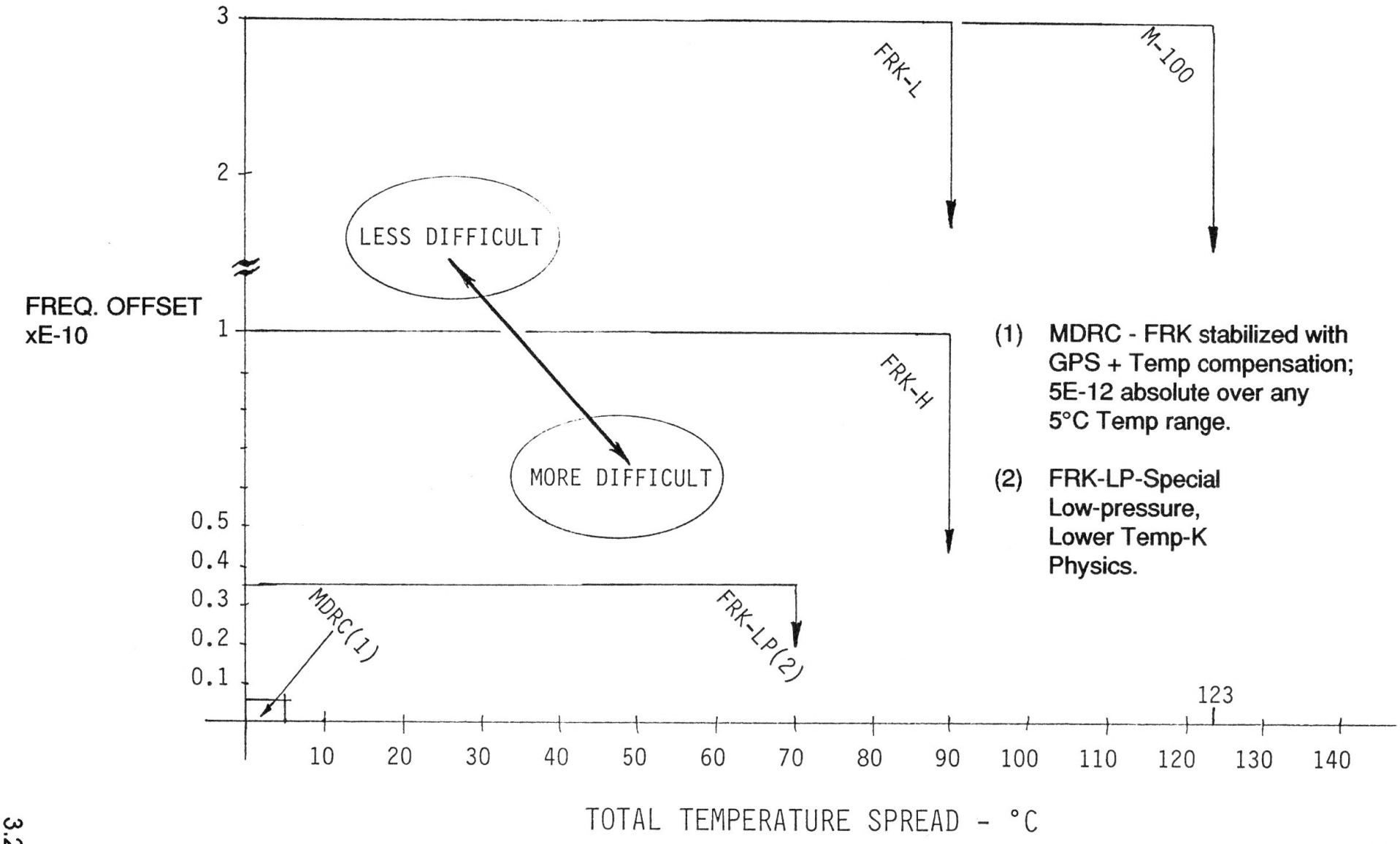
M100-HC TEMPERATURE COEFFICIENT, MEASURED DATA

Ball Efratom Division



FRK, M100, MDRC TEMPERATURE COEFFICIENT vs. TOTAL TEMP. SPREAD

Ball Efratom Division



(1) MDRC - FRK stabilized with GPS + Temp compensation; 5E-12 absolute over any 5°C Temp range.

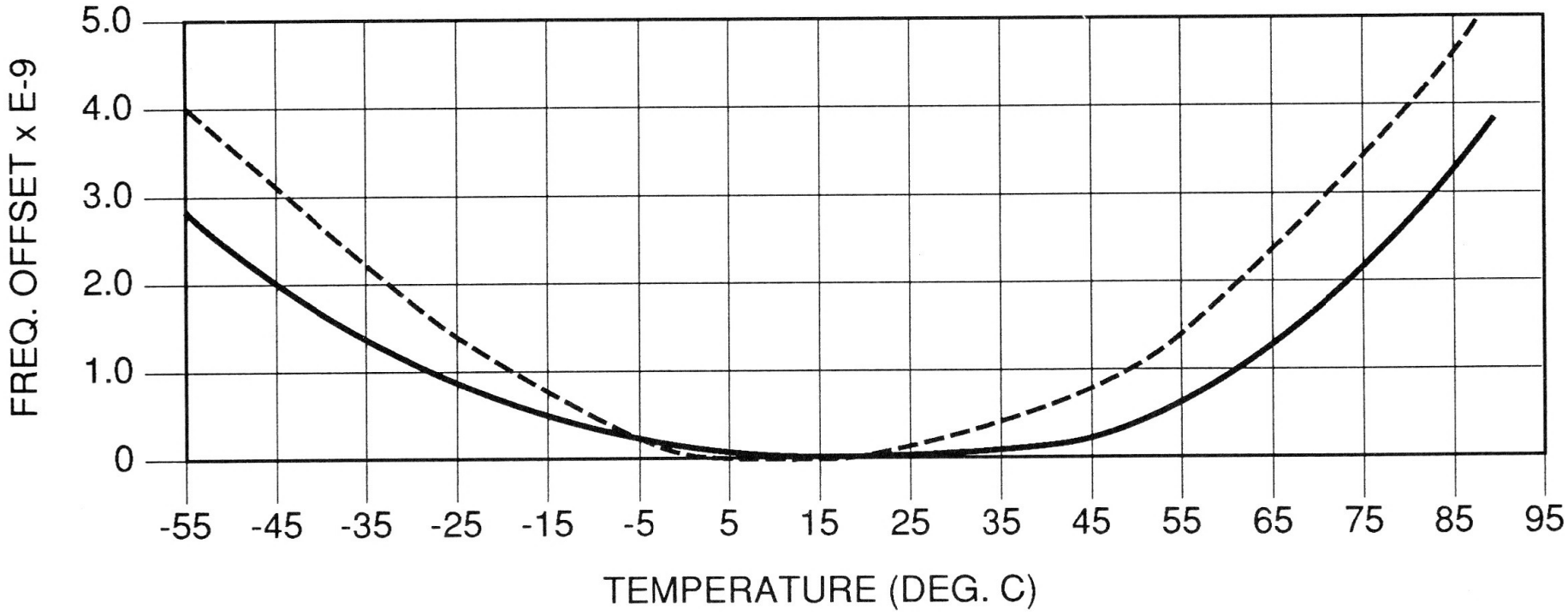
(2) FRK-LP-Special Low-pressure, Lower Temp-K Physics.

12/91

EMXO TEMPERATURE COEFFICIENT

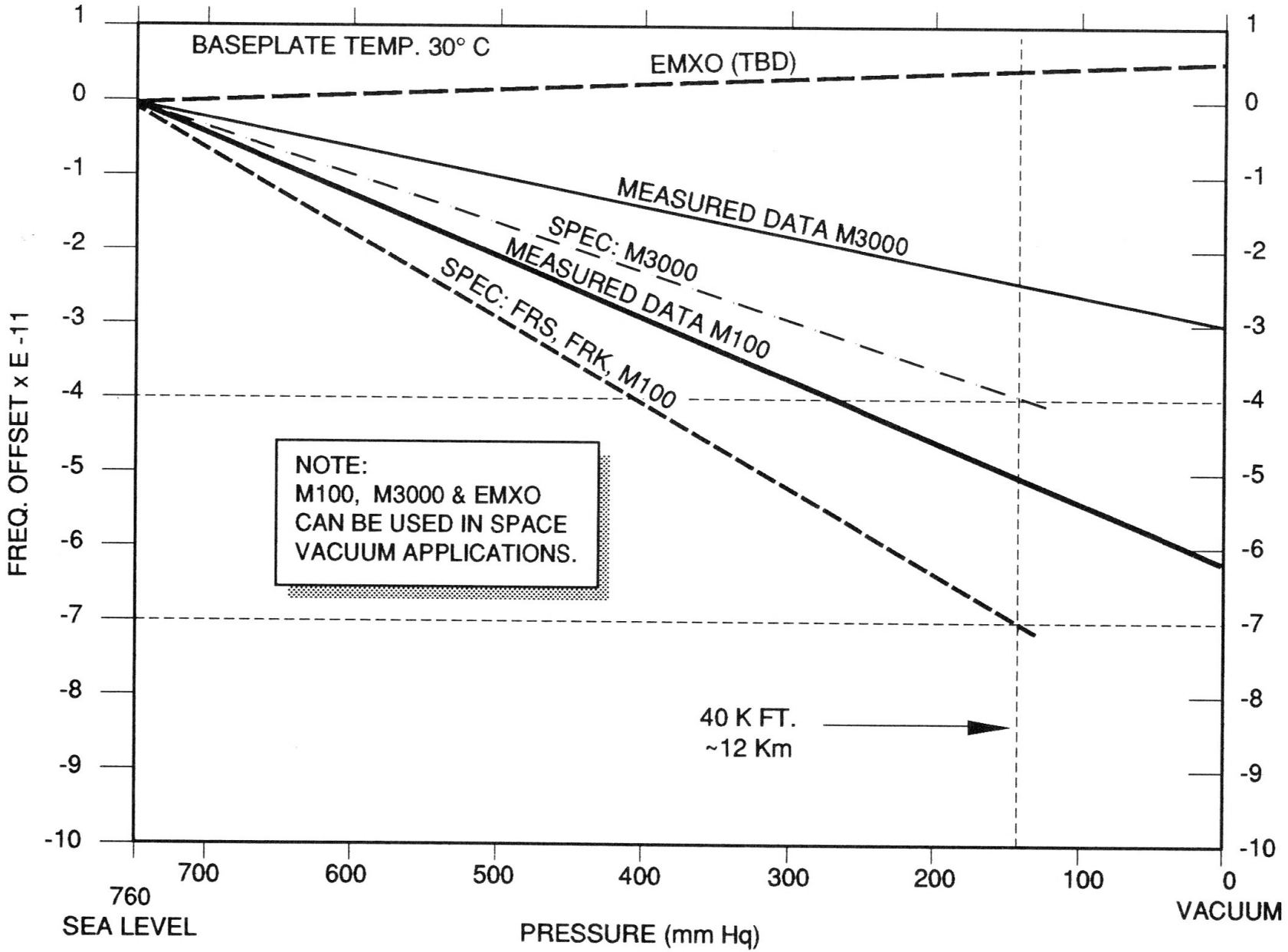
Ball Efratom Division

- 10 MHz, 110° C CRYSTAL RESONATOR
- EFC = OVdc
- TYPICAL



FRS, FRK, M100, M3000, EMXO
PRESSURE SENSITIVITY

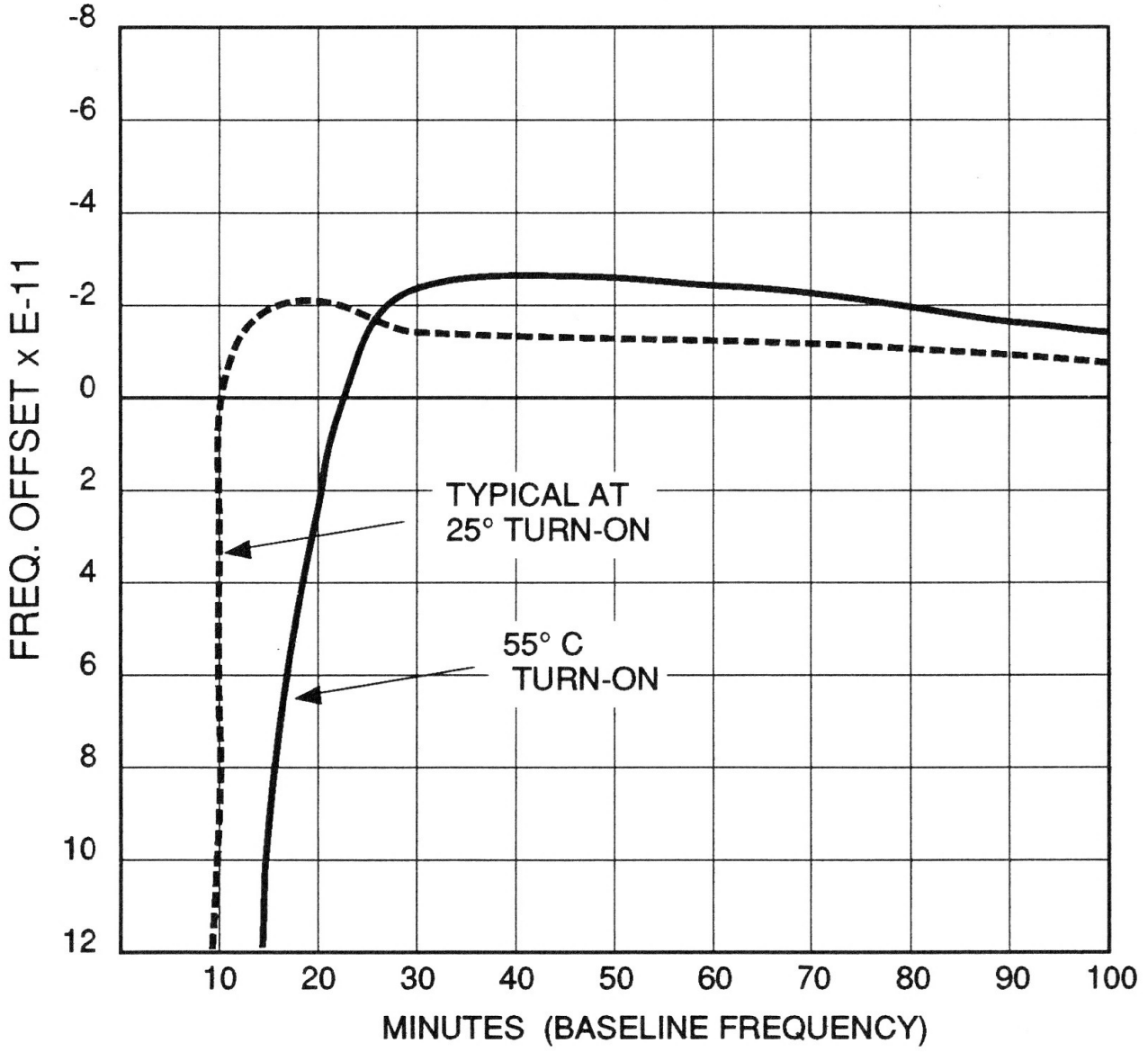
Ball Efratom Division



12/91

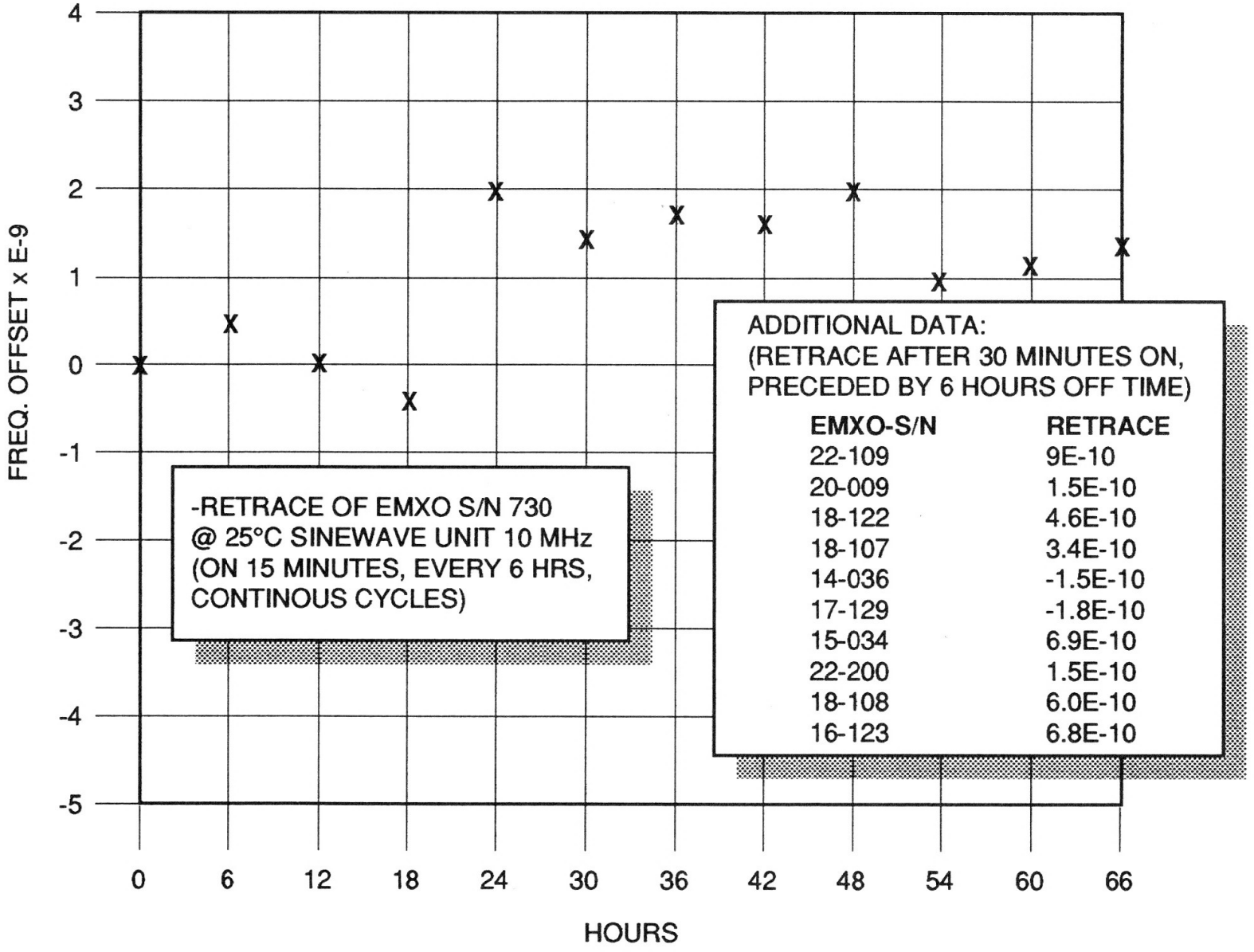
FRK, M100 TYPICAL RETRACE CHARACTERISITICS

Ball Efratom Division



EMXO TYPICAL RETRACE CHARACTERISTICS

Ball Efratom Division



FRK, FRT RUBIDIUM OSCILLATOR RELIABILITY DATA

Efratom Division

TABLE A-4/G.811

Rubidium clocks

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
HP5065A (1970)	159	21	7.6	120	31
EFRATOM → FRT/FRK (1973)	584	52	11.2	90	159
XSRM (1972)	71	13	5.5	90	15
P01 (1976)	44	41	1.08	–	20

Table A-7/G.811 shows the distributions of failures among the various sub-assemblies of caesium clocks based on user and manufacturer reports. The data on the HP units are taken from Johnson *et al.* [1980].

A comment is in order on the bias appearing between user and manufacturers reports, especially in Table A-3/G.811. We can be sure that the manufacturer has done his best in order to report real and correct figures. However, there are always some users who repair some minor faults in their own facilities without reporting these actions to the manufacturer. Thus, some bias is practically inevitable. Improvement of the feedback loop on failures and repairs would serve the interests of both manufacturers and users.

The data collected until now cover only a fraction of the world population of precision clocks. No peak has been observed in the first year of operation of caesium clocks, i.e. the "early failures" seem to have been eliminated by the burn-in process performed by the manufacturers.

Courtesy of: INTERNATIONAL TELECOMMUNICATION UNION
CCITT The International Telegraph & Telephone Consultative Committee
Red Book Volume III - Fascicle III.3
Digital Networks Transmission Systems and Multiplexing Equipment
Recommendations G.700-G.956
VIIIth Plenary Assembly/Malaga-Torremolinos, 8-19 October 1984
Geneva 1985

FRK, FRT RUBIDIUM OSCILLATOR RELIABILITY DATA (CONTINUED)

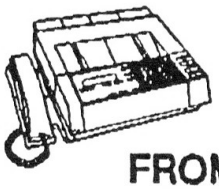
Ball Efratom Division

TABLE II – *Rubidium clocks*

Model (year)	ΣU	ΣF	MTBF (years)	MTTR (days)	No. of units in survey
HP5065A (1970)	119	18	6.61	140	16
EFRATOM →→ FRT/FRK (1973)	83	18	4.61	90	17
XSRM (1972)	67	12	5.58	90	14
P 01 (1976)	44	41	1.08	–	20

Courtesy of: INTERNATIONAL TELECOMMUNICATION UNION
CCIR International Radio Consultative Committee
Recommendations and Reports of the CCIR, 1982
(Also questions, Study Programmes, Resolutions, Opinions and Decisions)
XVth Plenary Assembly/Geneva, 1982
Volume VII
Standard Frequencies and Time Signals/Geneva 1982

NAVSTAR #3 Rb AFTER BEING OFF FOR 13 YEARS



TO: Mr. William Smith
ORG. Efratom Ball Division
FAX No. 714/770-2463

FROM: David W. Allan; Tel. No. (303) 497-5637
Time & Frequency Div.; NIST / Boulder, CO 80303
FAX No. (303) 497-6461; No. of pages (with cover) 4

TEXT Date July 23, 1991

Mr. William Smith
Efratom Ball Division
FAX (714)770-2463

Dear Bill,

Per your request, please find the analysis of NAVSTAR 3 (PRN-6) rubidium. It was turned on 26 June 1991 (day number 177) of this year. It had been off thirteen years. The first plot of frequency shows a very large frequency step for the first day. I am not absolutely sure that this is a valid data. If it is, you can see that it came up within 2½ parts in 10^{10} of nominal frequency. After the first day, it stabilized quite well with a sightly positive frequency drift. As you can see, it started out with it's frequency too high, and then after a day went to about -5×10^{-11}. The frequency stability plot, $\sigma_y(\tau)$, after removing the frequency drift is exceptional. In other words, five days after it was turned on, the clock has settled out to a exceedingly good behavior. Better than essentially all the clocks that we have looked at of that type.

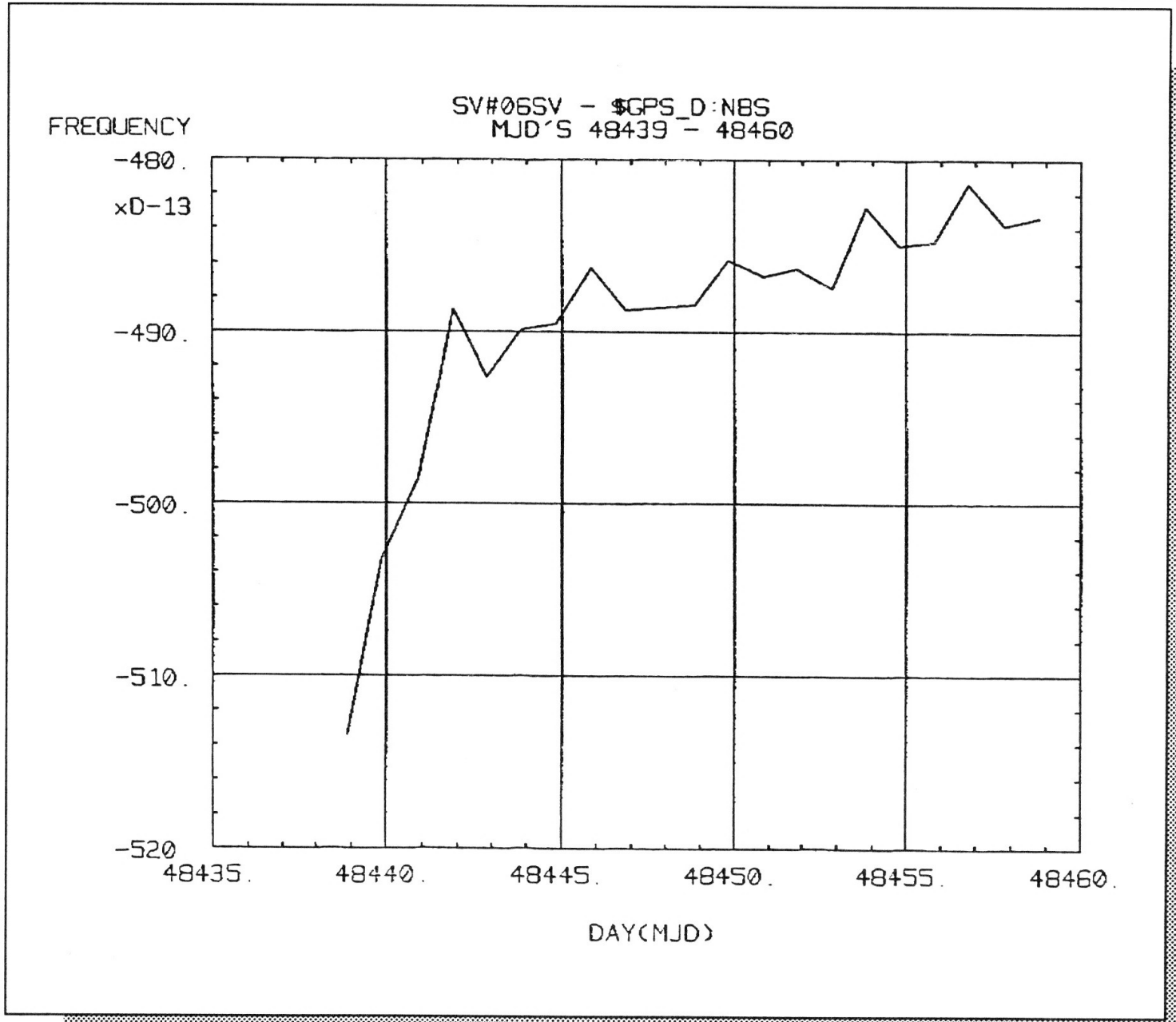
I hope this information is useful. I am sure Phil Talley can help you further. His telephone number (in case you do not have it) is (213)336-0484.

Best regards,

David W. Allan
Time and Frequency Division

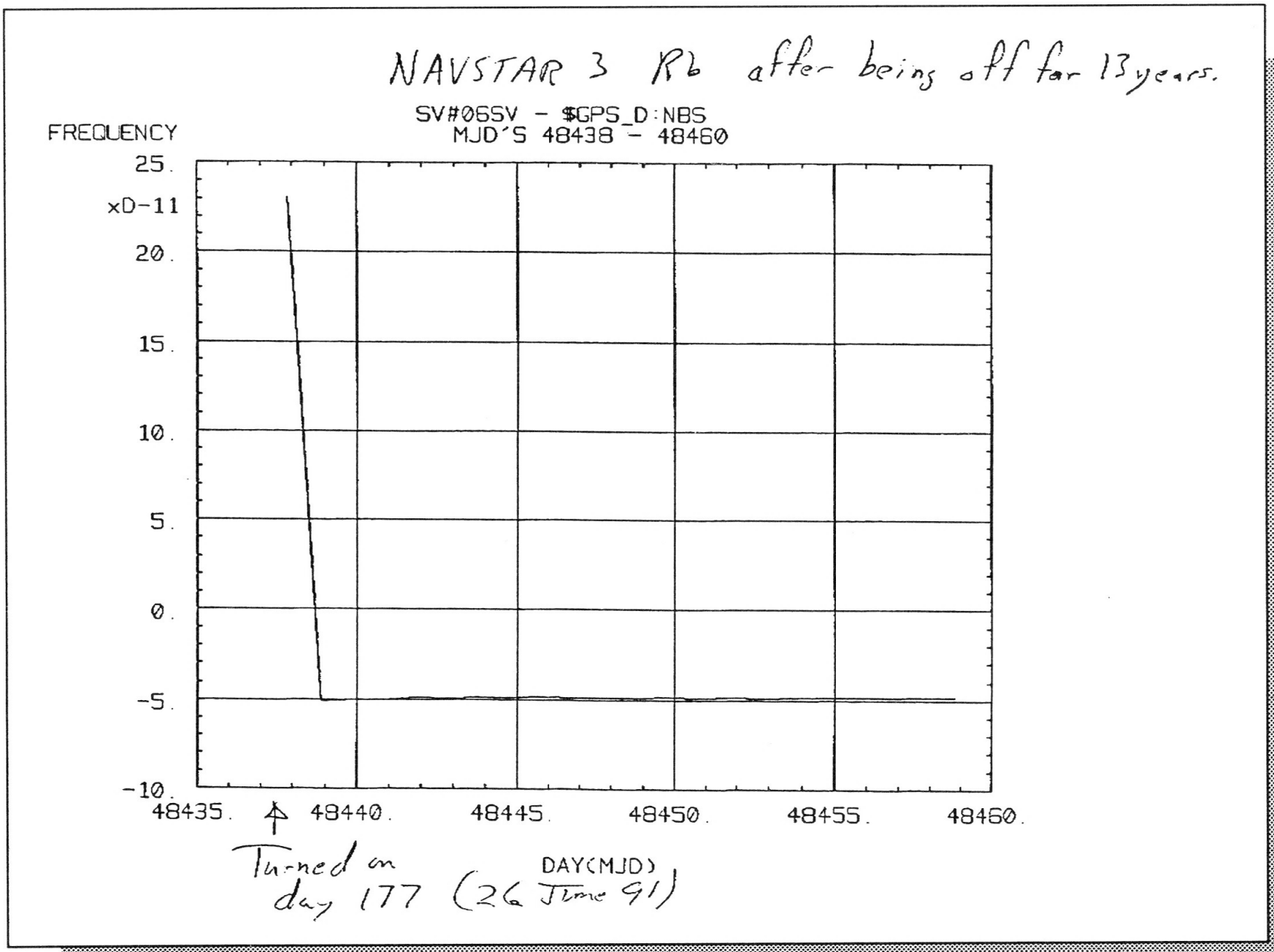
NAVSTAR #3 Rb AFTER BEING OFF FOR 13 YEARS

Ball Efratom Division



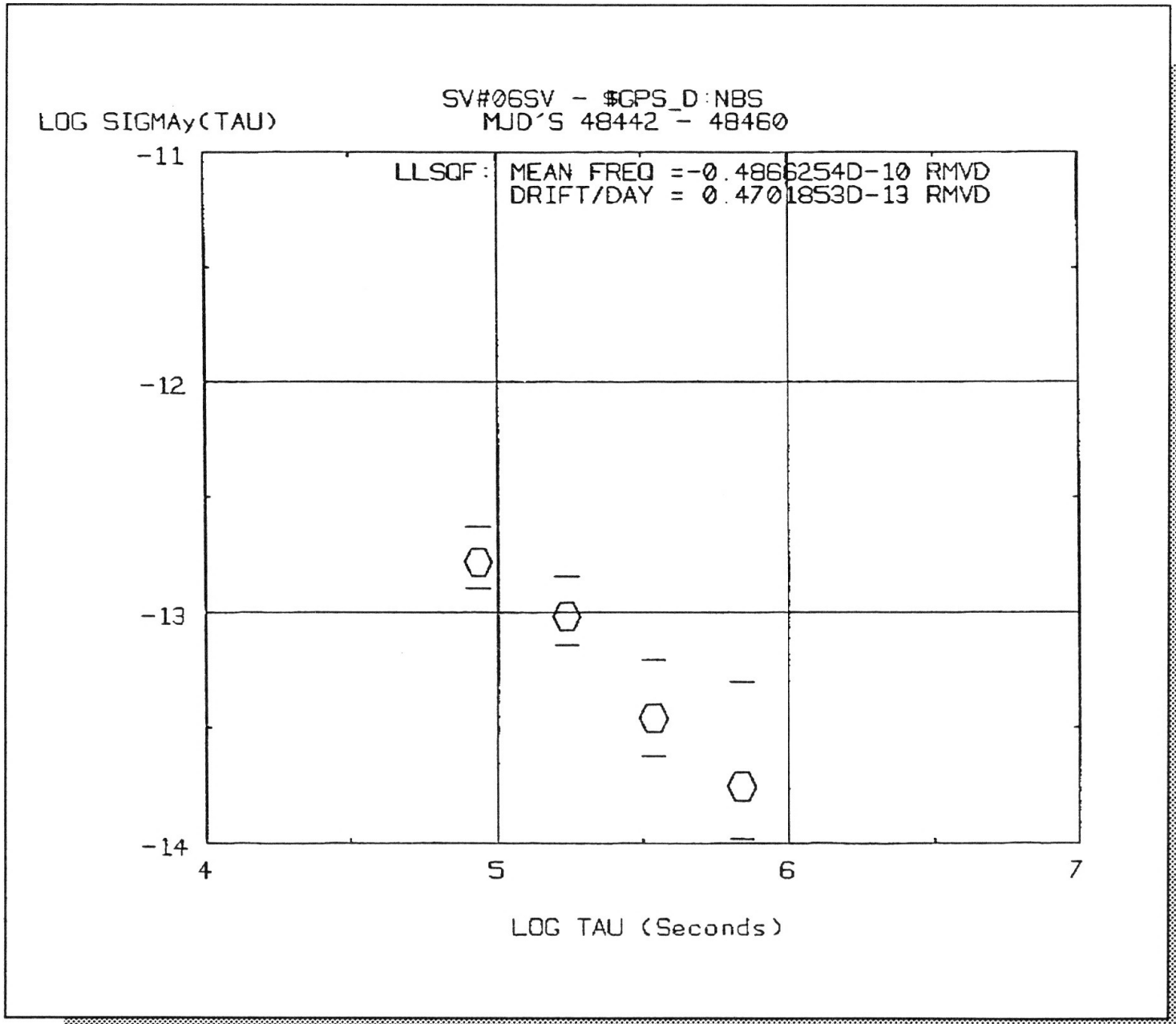
NAVSTAR #3 Rb (Continued)

Ball Efratom Division



NAVSTAR #3 Rb (Continued)

Efratom Division



EMXO RELIABILITY ANALYSIS

Ball Efratom Division

ENVIRONMENT @ 50°C	MTBF (HOURS) OVEN @ 90°c	MTBF (HOURS) OVEN @ 110°C
AIRBORNE INHABITED CARGO (AIC)	334,768	220,575
AIRBORNE UNINHABITED FIGHTER (AUF)	84,253	58,378
AIRBORNE, ROTARY WINGED (ARW)	104,066	70,465

MIL-STD-704 ELECTRICAL POWER SPEC COMPATIBILITY FOR M100

Ball Efratom Division

MIL-STD-704 SPEC REQUIREMENTS					
SPEC	NORMAL	ABNORM	DROPOUT	TRANSIENT	RIPPLE
704A CAT. B	24-28.5 Vdc	22.5-30 Vdc	7 sec	600V, 10µs 80V, 50ms	2VP-P
704C	22-29 Vdc	20-31.5 Vdc	5 sec	50V, 45ms	1.5VP-P
M100 COMPATIBILITY FOR 704 SPEC					
ELEC. BUS	22.5-32 Vdc	20.5-32 Vdc	100µS	50V, 50ms	YES
HTR BUS	22.5-32 Vdc	20.5-32 Vdc	10 SEC	50V, 50ms	YES
STATUS	YES	704A - YES, 704C - NO	ELEC. BUS - NO HTR BUS - YES	704A - YES, 704C - NO	YES

MIL-STD-704 ELECTRICAL POWER SPEC COMPATIBILITY FOR M3000

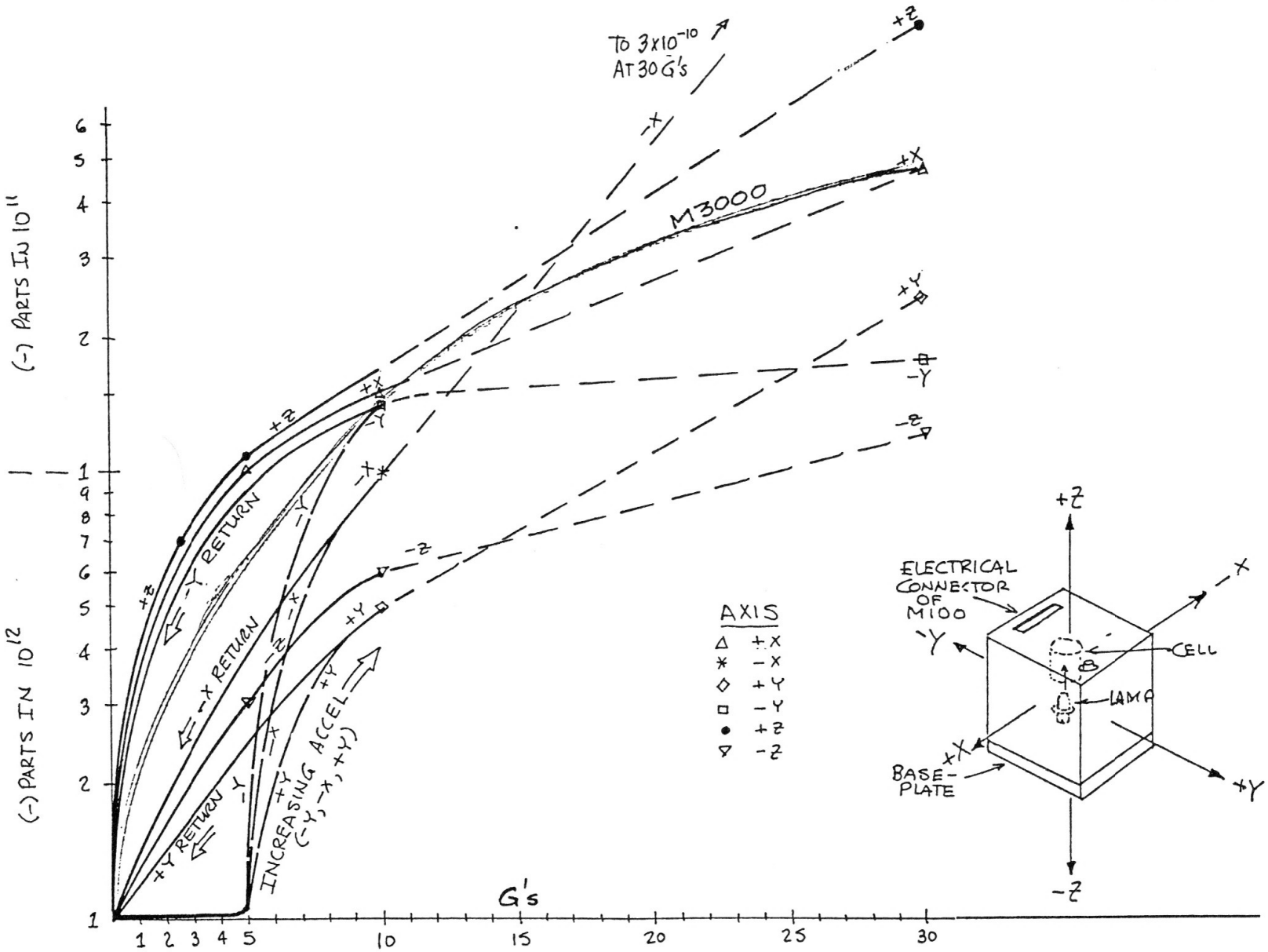
Ball Efratom Division

SPEC	NORMAL	ABNORM	DROPOUT	TRANSIENT	RIPPLE
704A CAT. B	24-28.5 Vdc	22.5-30 Vdc	7 sec	600V, 10μs 80V, 50ms	2 VOLTS
704C	22-29 Vdc	20-31.5 Vdc	5 sec	50V, 45ms	1.5 VOLTS
M3000 DESIGN SUMMARY					
ELEC. BUS	22-32 Vdc	20.5-32 Vdc	100μS	50V, 1 SEC	3 VPP
HTR BUS	22-32 Vdc	20-32 Vdc	10 SEC	600V, 10μS	3 VPP
COMPARISON M3000 vs. MIL-SPEC					
ELEC. BUS	YES, 704A, 704C	704A - YES, 704C - NO	NO, 704A, 704C	704A - NO, 704C - YES	YES, 704A, 704C
HTR BUS	YES, 704A, 704C	YES, 704A, 704C	YES, 704A, 704C	704A - YES, 704C - NO	YES, 704A, 704C

ACCELERATION & VIBRATION

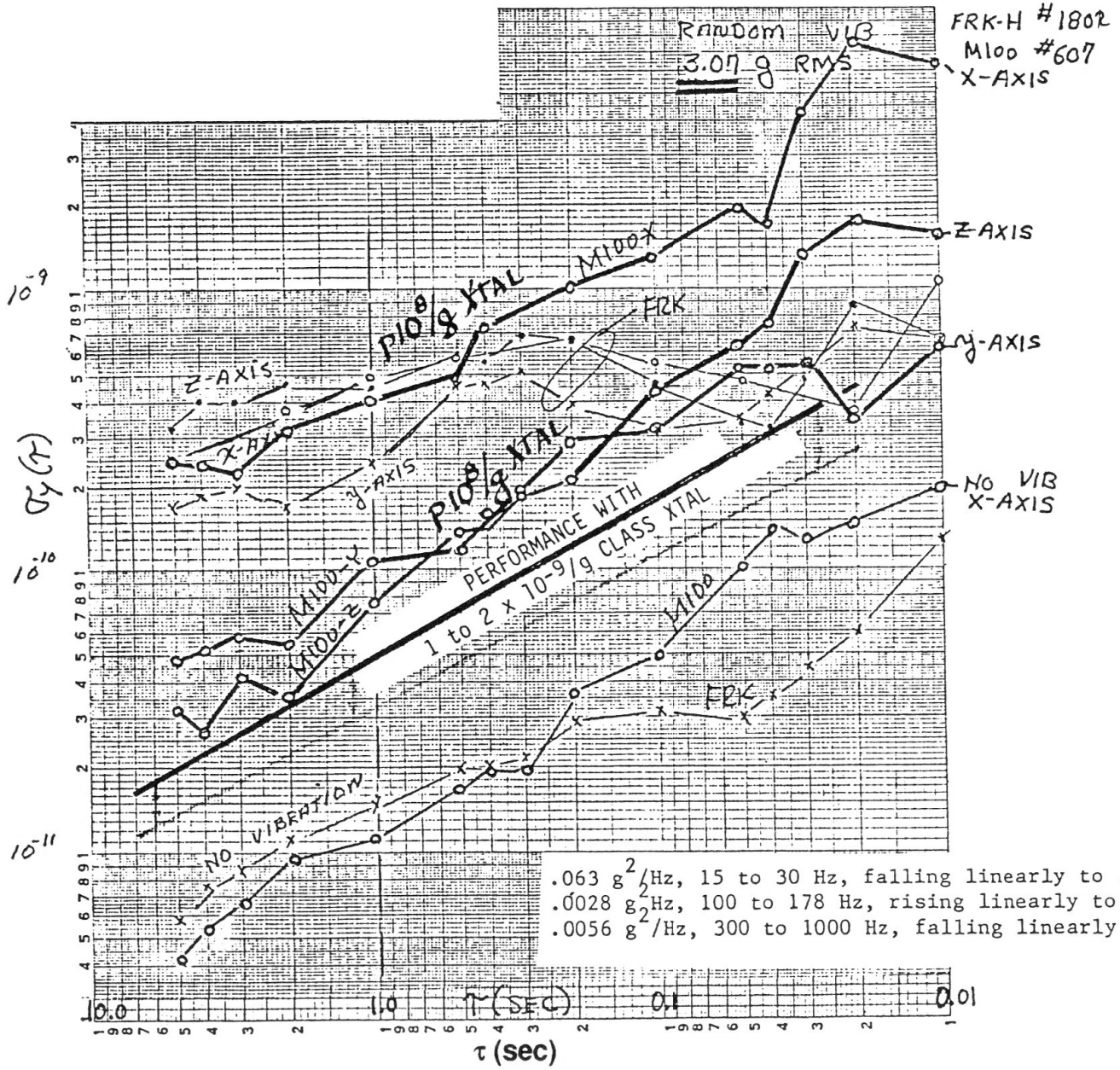
M100, M3000 LINEAR ACCELERATION

Ball Efratom Division



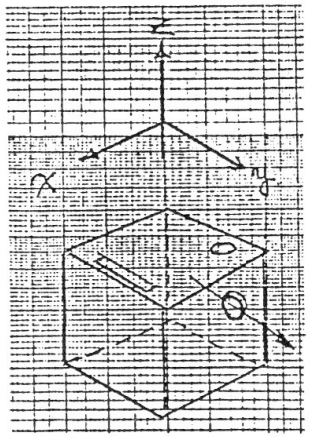
FRK, M100 RANDOM VIBRATION vs. ALLAN VARIANCE, MEASURED DATA

Ball Efratom Division



WITH MODELS
FRK & M-100
250-1816
607

(IBM DATA)

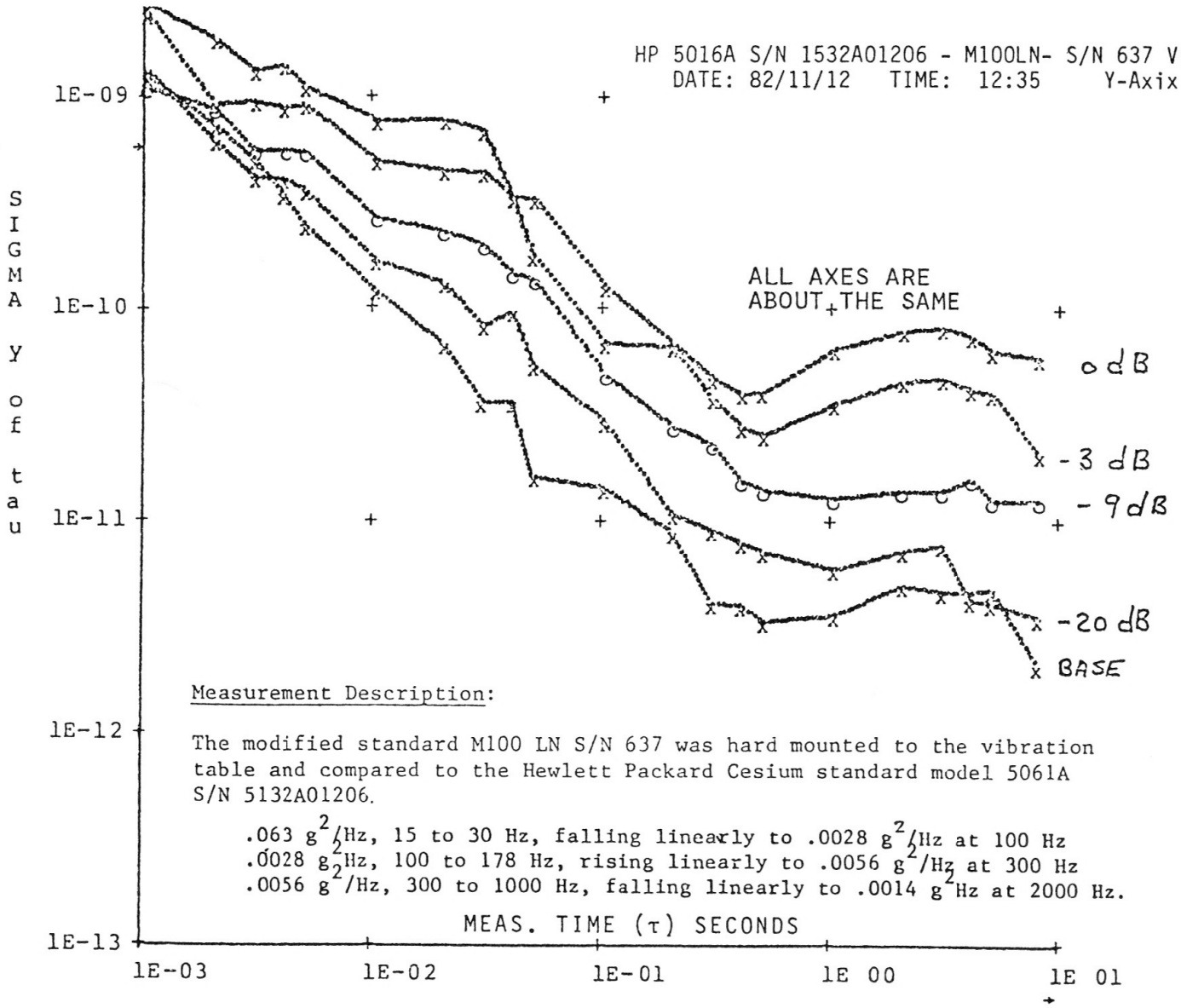


CRYSTAL DISC NORMAL TO "Y"/"X" PLANE

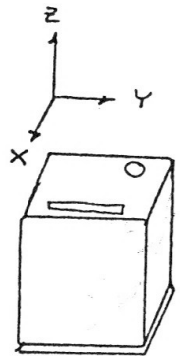
.063 g^2/Hz, 15 to 30 Hz, falling linearly to .0028 g^2/Hz at 100 Hz
.0028 g^2/Hz, 100 to 178 Hz, rising linearly to .0056 g^2/Hz at 300 Hz
.0056 g^2/Hz, 300 to 1000 Hz, falling linearly to .0014 g^2/Hz at 2000 Hz.

M100-LN, S/N 637 RANDOM VIBRATION vs. ALLAN VARIANCE, MEASURED DATA

Ball Efratom Division



(IBM DATA)



$<2 \times 10^{-9}$/g
SC-CUT Crystal
3.07gRMS

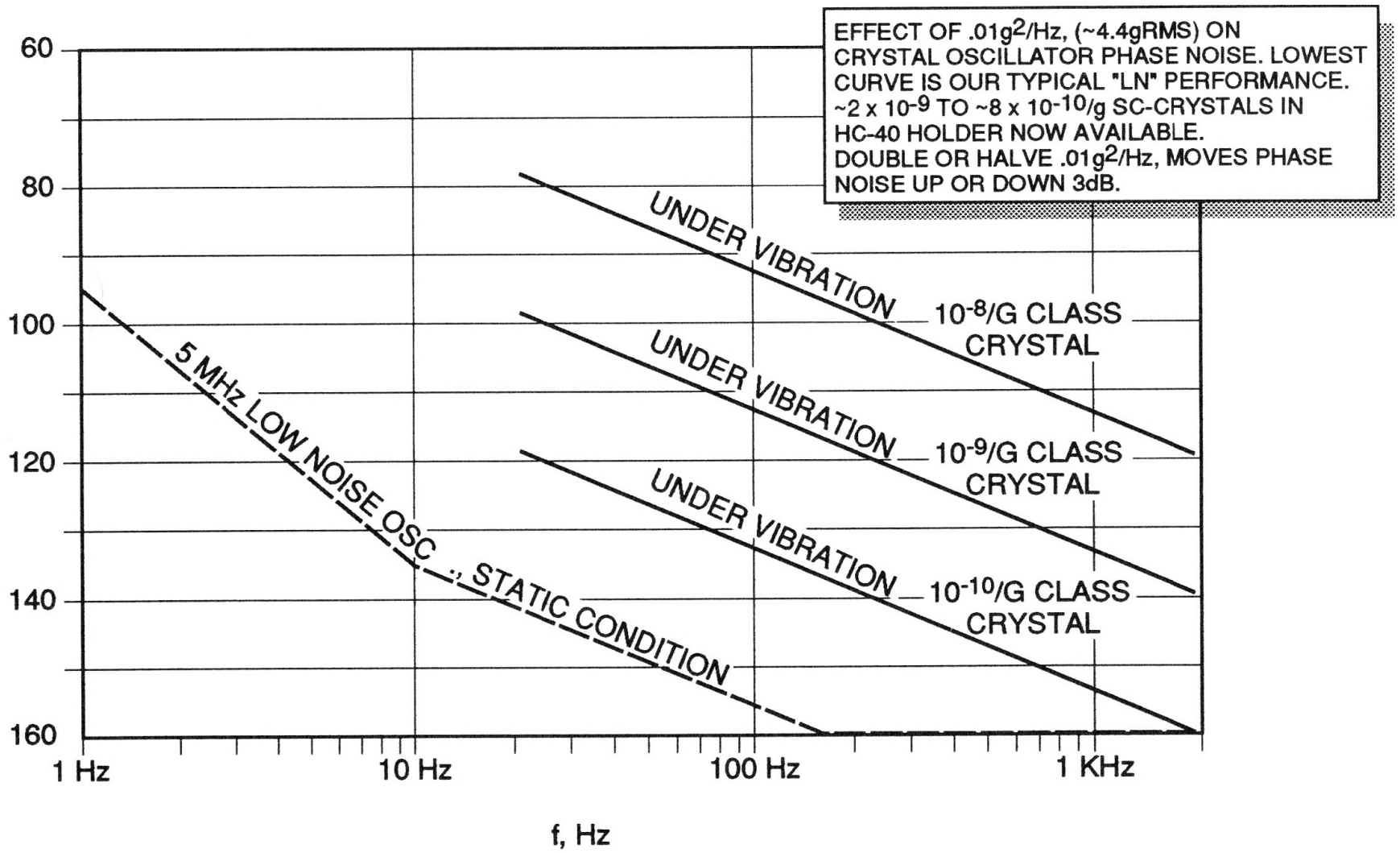
Measurement Description:

The modified standard M100 LN S/N 637 was hard mounted to the vibration table and compared to the Hewlett Packard Cesium standard model 5061A S/N 5132A01206.

.063 g^2/Hz, 15 to 30 Hz, falling linearly to .0028 g^2/Hz at 100 Hz
.0028 g^2/Hz, 100 to 178 Hz, rising linearly to .0056 g^2/Hz at 300 Hz
.0056 g^2/Hz, 300 to 1000 Hz, falling linearly to .0014 g^2/Hz at 2000 Hz.

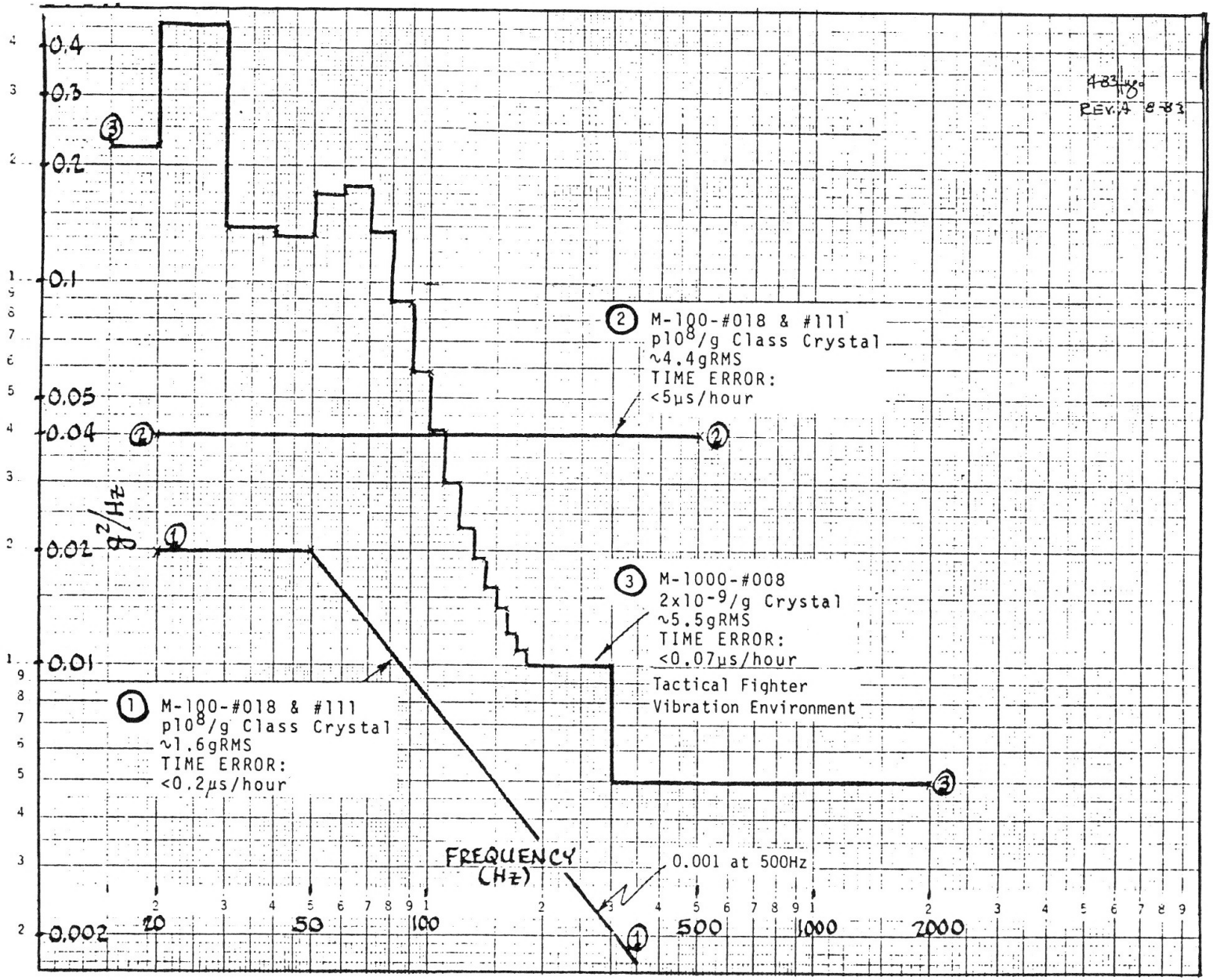
RANDOM VIBRATION vs. PHASE NOISE, BASIC Rb PRODUCT

Ball Efratom Division



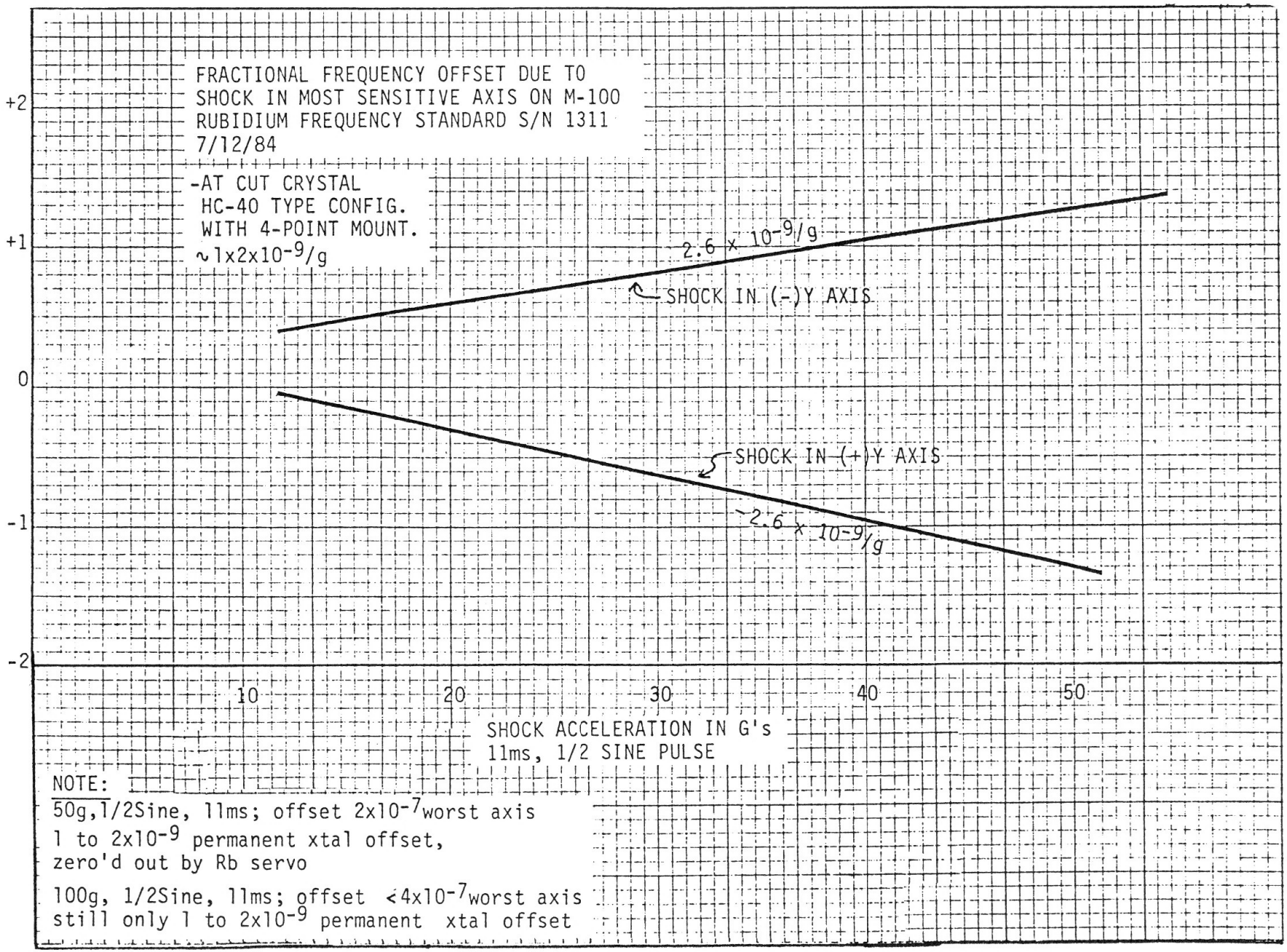
M100, M3000 RANDOM VIBRATION vs. TIME ERROR

Ball Efratom Division



M100 SHOCK vs. FREQUENCY OFFSET

Ball Efratom Division



12/91

EMXO G-SENSITIVITY

Ball Efratom Division

TYPICAL G-SENSITIVITY DATA

UNIT #	X	Y	Z	GAMMA
1020	4.5	0.7	4.9	6.7
1021	9.1	1.0	7.7	12.0
1017	1.0	1.0	0.7	1.6
1030	4.2	0.3	1.7	4.5
1019	2.4	1.4	0.0	2.8
1028	1.4	1.0	2.8	3.3
1021	3.1	1.8	0.3	3.6
1025	4.5	3.5	0.7	5.7
1032	2.8	2.4	1.4	3.9
1035	0.3	0.7	5.2	5.3
1029	5.2	2.1	0.7	5.7
1037	4.2	0.3	3.5	5.5
1024	4.2	2.8	0.7	5.1
1022	3.5	0.7	1.4	3.8
1023	1.4	1.4	0.3	2.0
1018	1.0	2.4	1.4	3.0
1026	7.0	0.7	1.0	7.1
1031	1.4	1.8	3.1	3.8
1036	4.5	0.3	3.5	5.7
1033	1.0	1.0	2.8	3.1
1034	3.1	3.1	1.0	4.5
AVG.	3.3	1.4	2.1	4.7

Z-G TIP-OVER TEST
(NORMALIZED TO 1G)
SCALE x 10^{-10}/g

Rb Radiation Hardening Data

General Information

1. The Efratom Rb oscillators have been tested and analyzed for radiation hardness.

   A. Unhardened commercial FRK production units have been subjected to total dose and dose-rate environments.

   B. Hardened military M100, M3000 production units have been subjected to combined total dose/neutron fluence environments as well as dose-rate in various environments.

   C. Physics package glass components and photo cells have been subjected to a total dose, dose-rate, and neutron environments at the piece-part level.

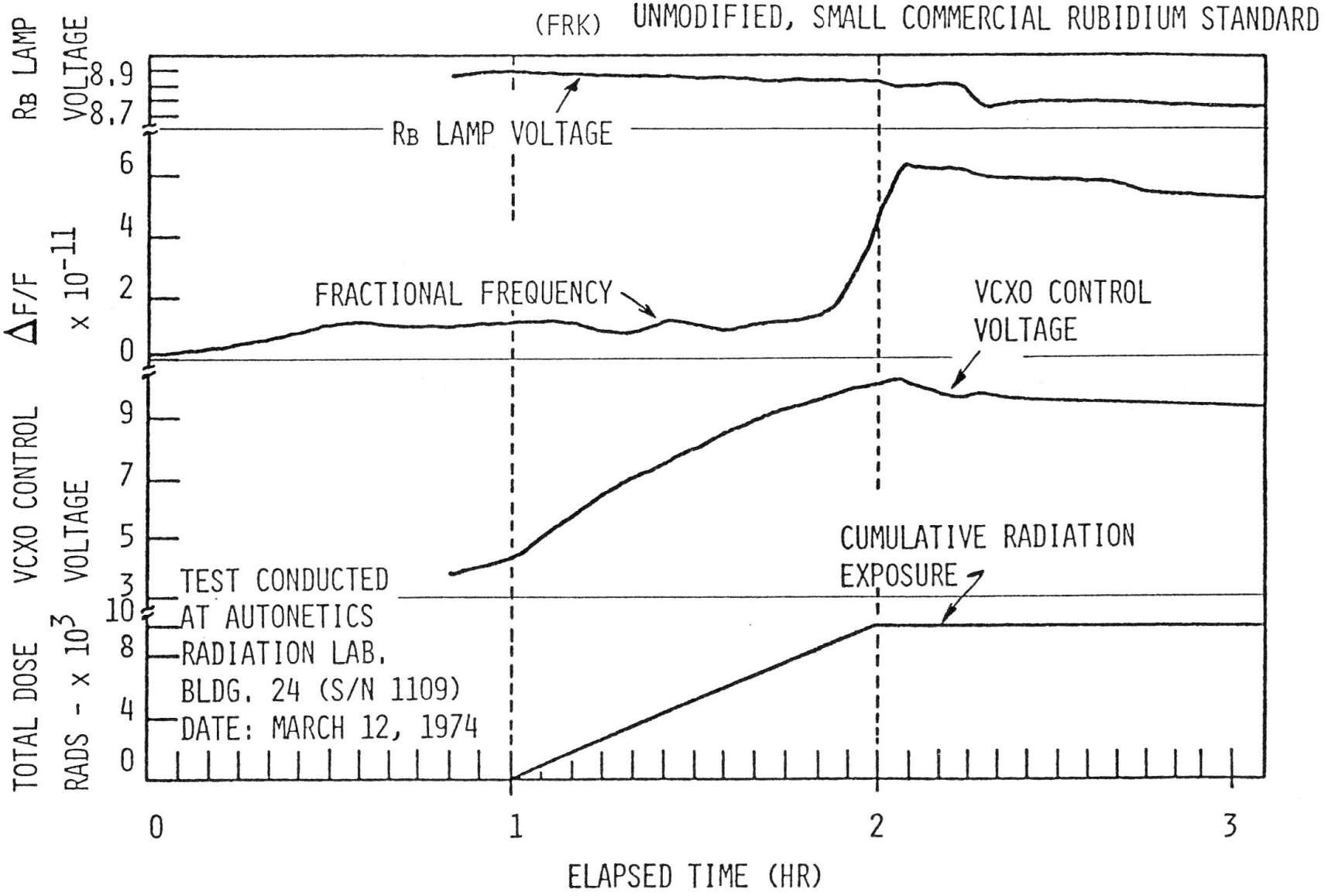
   D. The Efratom military M100, M3000 Rb oscillators have been analyzed for radiation hardness, based on available electronic piece-part radiation data and unit-level radiation test data from above tests (report available on request).

2. The M100, M3000 military Rb oscillators are hardened to the most stringent ground tactical and space radiation environments for dose rate as well as combined total dose/ neutron fluence levels.

3. The following data provide an overview of the above.

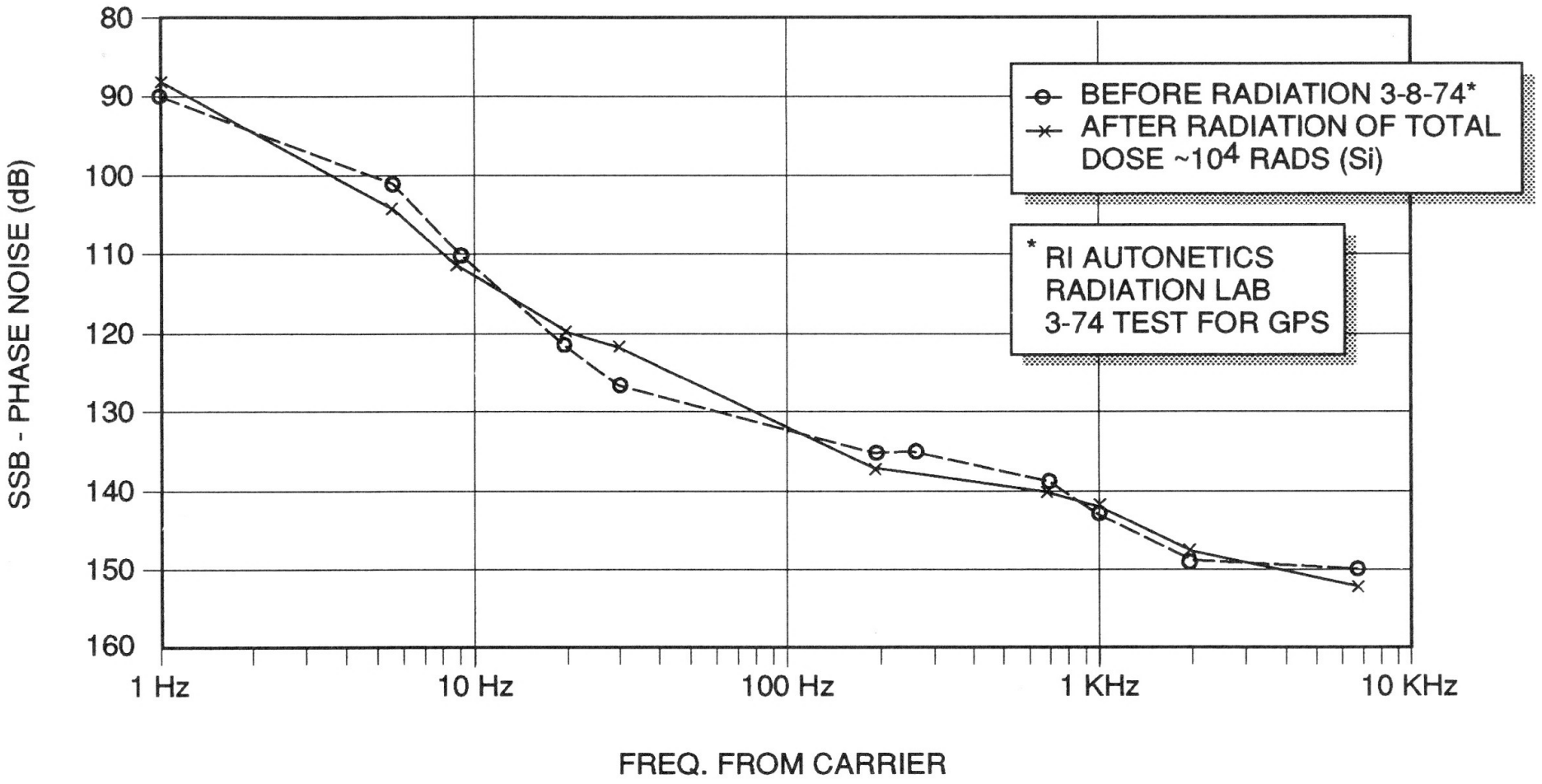
EFFECT OF 10^4 RADS (CO^{60}) ON AN OPERATING Rb OSC., COM'L FRK, MEAS. DATA

Ball Efratom Division



FRK PHASE NOISE vs. RADIATION DOSE, MEAS. DATA

Ball Efratom Division



FRK NAVSTAR-GPS Rb OSCILLATOR DOSE RATE

Effect of Nuclear Radiation (Dose Rate) on an Operating Rubidium Frequency Standard

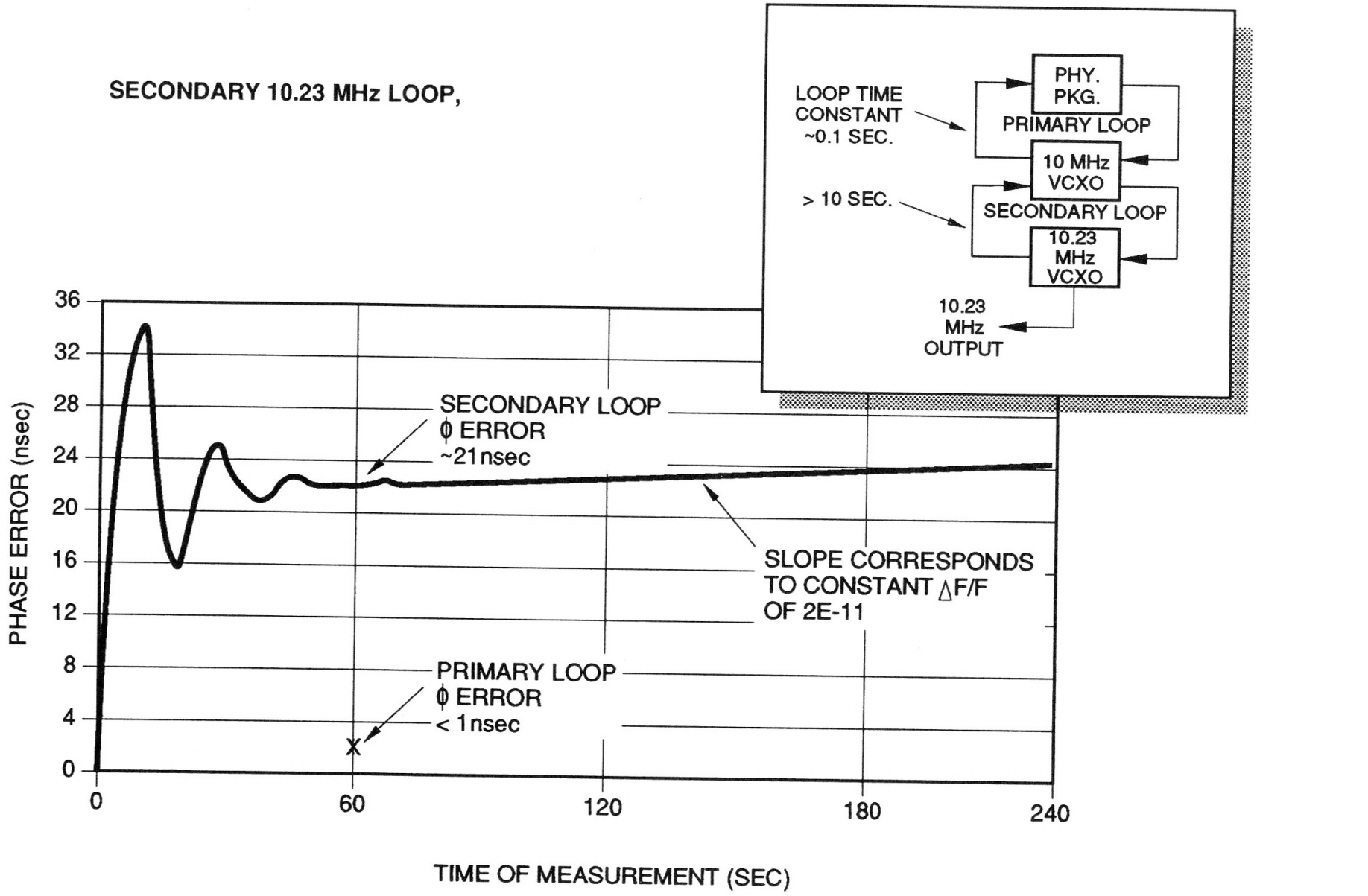
Device Tested:	Unshielded GPS Phase I Rubidium Space Clock (EM3) (Com'l FRK)
Location of Test:	Rockwell International, Autonetics Division, Flash X-ray Facility
Dose Rate:	>3.8E-8 RAD (Si)/SEC

Results

- Effect of radiation on physics package: negligible
- Accumulated phase error: <1 nsec (primary loop)

FRK NAVSTAR-GPS Rb OSCILLATOR PHASE ERROR

Ball Efratom Division



M100 GAMMA FLASH RADIATION TEST, MEAS. DATA

Ball Efratom Division

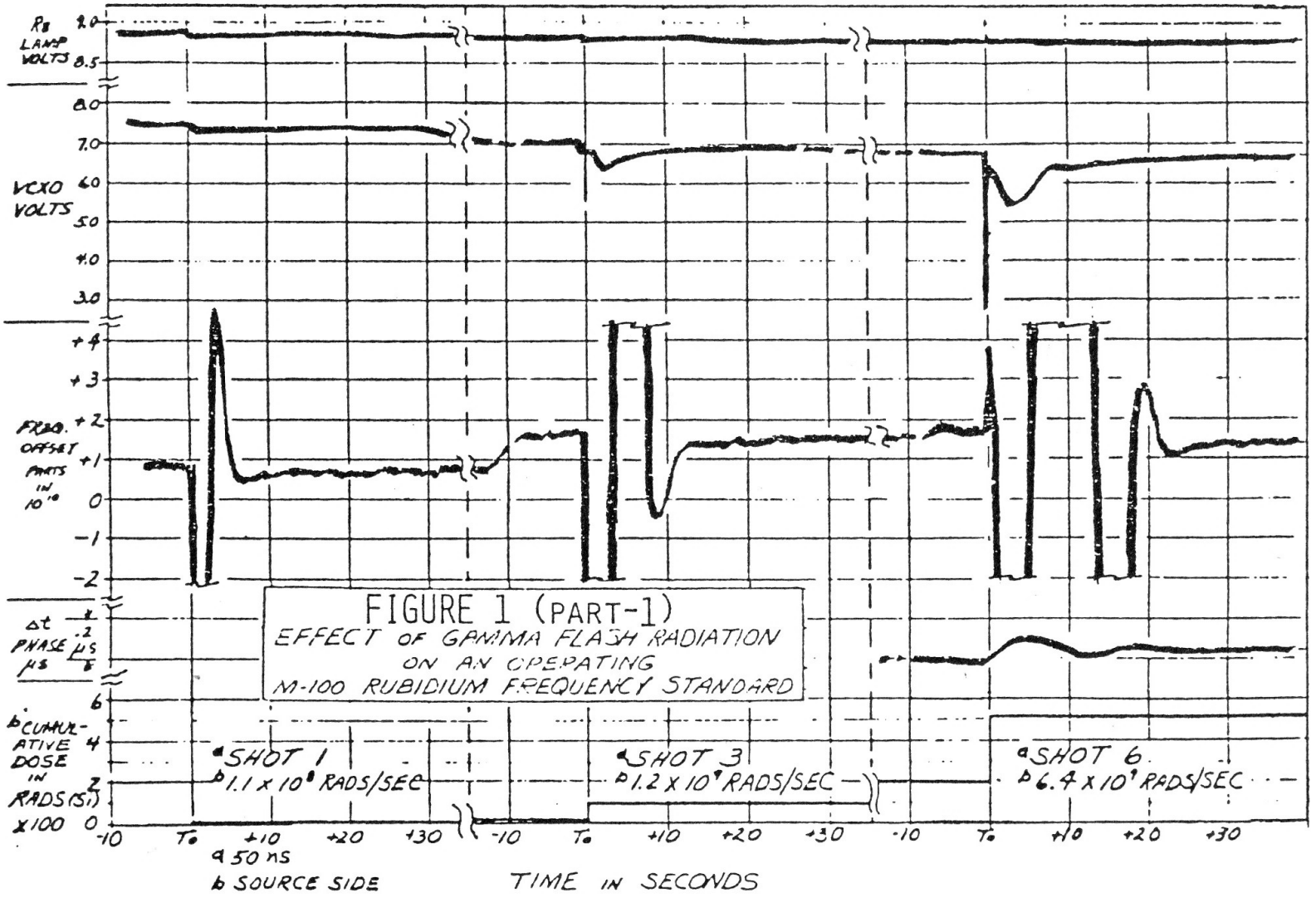


FIGURE 1 (PART-1)
EFFECT OF GAMMA FLASH RADIATION ON AN OPERATING M-100 RUBIDIUM FREQUENCY STANDARD

NOTE: MODEL M-100LN (LOW NOISE UNIT: SERVO LOOP TIME ~1 TO 3.0 SEC VS. STANDARD UNIT ~200 TO 500 ms)

M100 GAMMA FLASH RADIATION TEST (CONTINUED)

Ball Efratom Division

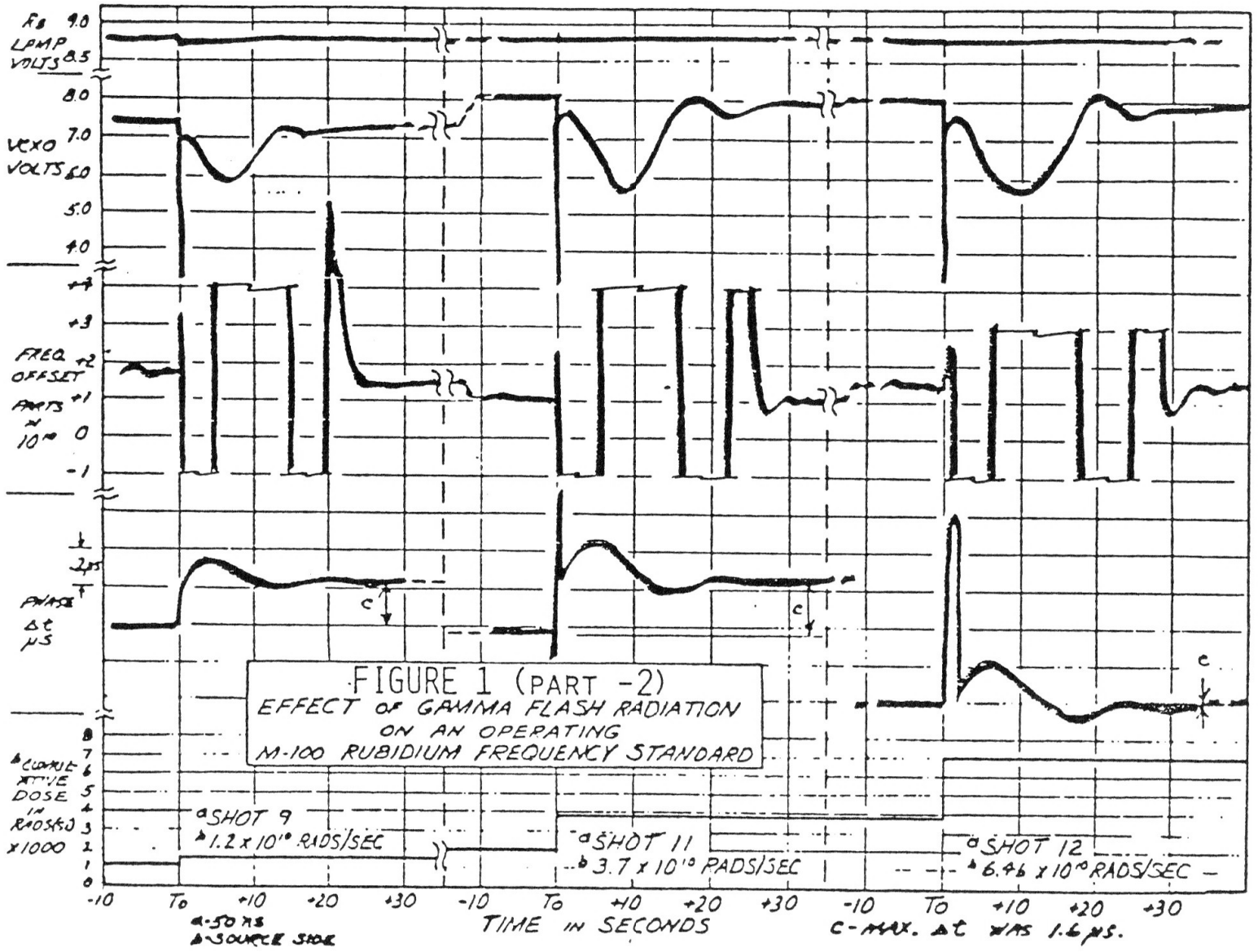


FIGURE 1 (PART -2)
EFFECT OF GAMMA FLASH RADIATION ON AN OPERATING M-100 RUBIDIUM FREQUENCY STANDARD

NOTE: MODEL M-100LN (LOW NOISE UNIT: SERVO LOOP TIME ~1 TO 3.0 SEC VS. STANDARD UNIT ~200 TO 500 ms)

FOR STANDARD UNIT, SCALE TIME OF ABOVE BY ~10

M100 GAMMA FLASH RADIATION TEST DATA - 50 nsec FLASH (CONTINUED)

Ball Efratom Division

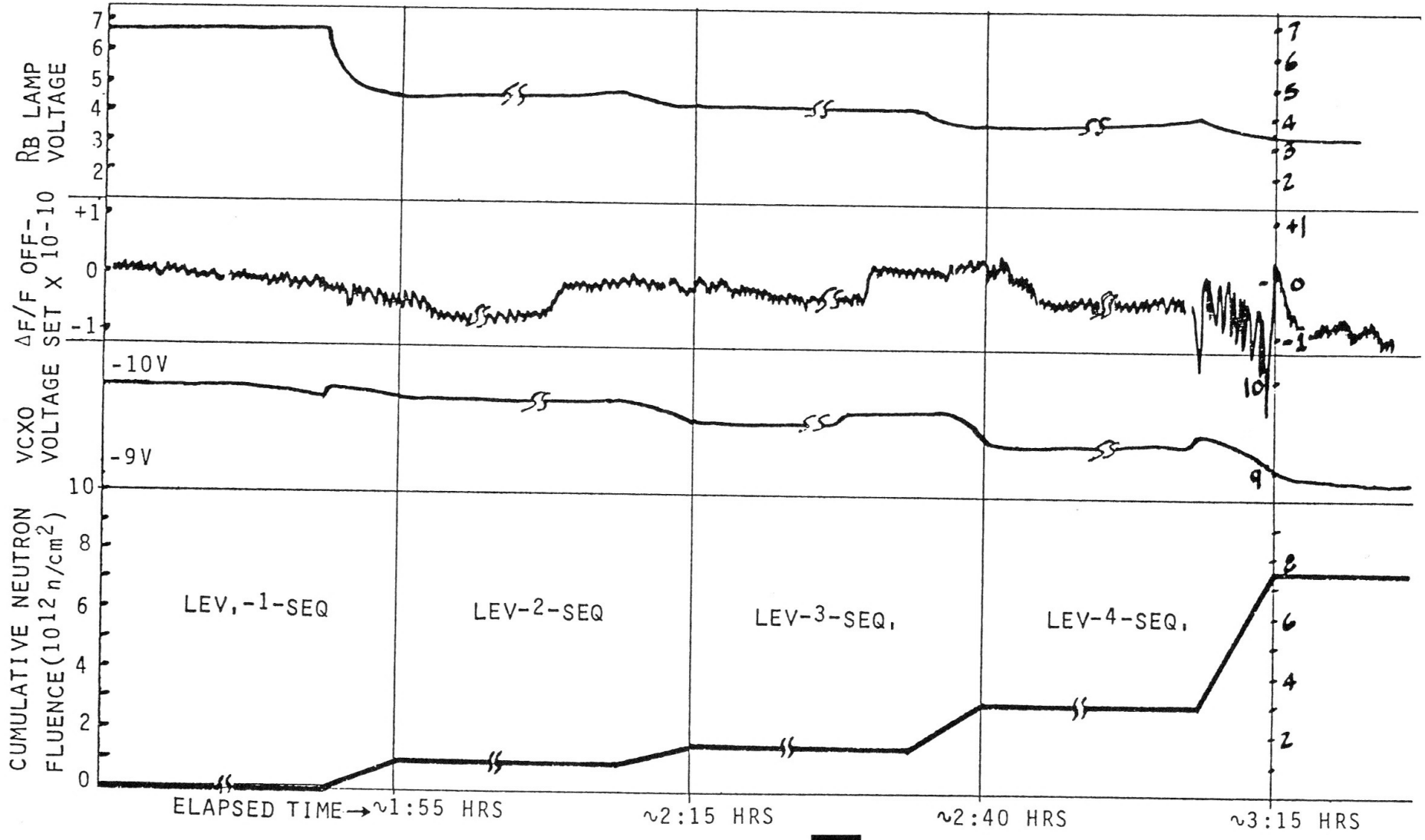
S/N 650 Shot No.	Source (Servo) Side: Average Dose -Rads(Si)	Source (Servo) Side: Rads(Si) Per Second	Opposite Side: Average Dose -Rads(Si)	Opposite Side: Rads(Si) Per Second	Frequency Offset: Offset After 1 Sec.	Frequency Offset: Offset After 2 Sec.	Recovery Time to $< 5 \times 10^{-11}$ -Seconds
1	5.61	1.122×10^{8}	3.27	6.54×10^{7}	-	-	6
2	14.08	2.816×10^{8}	6.32	1.264×10^{8}	-	-	$\sim$ 8
3	60.5	1.21×10^{9}	25.7	5.14×10^{8}	-	-	11
[a]4	22.8	4.56×10^{8}	53.1	1.062×10^{9}	-	-	12
5	96.7	1.934×10^{9}	41.9	8.38×10^{8}	-	-	14
6	319.0	6.38×10^{9}	113.1	2.262×10^{9}	2.1×10^{-8}	2.1×10^{-8}	20
7	465.8	9.316×10^{9}	157.2	3.144×10^{9}	4.77×10^{-8}	2.8×10^{-8}	21
[a]8	142	2.84×10^{9}	422	8.44×10^{9}	4.53×10^{-8}	3.48×10^{-8}	17
9	591	1.182×10^{10}	178	3.56×10^{9}	6.15×10^{-8}	3.67×10^{-8}	22
[a]10	261	5.22×10^{9}	888	1.762×10^{10}	5.88×10^{-8}	3.36×10^{-8}	19
11	1844	3.688×10^{10}	481	9.62×10^{9}	1.07×10^{-7}	6.22×10^{-8}	25
12	3230	6.46×10^{10}	662	1.324×10^{10}	[b] ~ 0	7.33×10^{-8}	28
TOTAL DOSE	7052.49		3024.59				
S/N 695							
13	516	1.03×10^{10}	167	3.34×10^{9}	9.2×10^{-8}	4.42×10^{-8}	42

a - the test unit was rotated 180° b - the offset crossed zero at 1 second.

EFFECT OF NEUTRONS, ~10^{13} n/cm^2 (Total Dose ~10^4 Rads) ON AN OPERATING M100, MEAS. DATA

Ball Efratom Division

TEST CONDUCTED ON AN UNMODIFIED PRODUCTION M-100, S/N #E002 AT IRT SAN DIEGO, CAL APRIL 22, 1982



ABERDEEN PULSED REACTOR
FAC. NEUTRON TESTS, M100 MEAS. DATA

Ball Efratom Division

TEST DAY	NEUTRON EXPOSURE	DELTA f/f AT TIME t	
		t AT 2 SEC.	t AT 10 SEC (RESIDUAL)
1ST DAY APRIL 9, 1984	1ST (LO-LEVEL)	$+7 \times 10^{-10}$	-1.9×10^{-11}
	2ND (HI-LEVEL) (2 HRS. LATER)	-1.3×10^{-9}	-3.8×10^{-11}
2ND DAY APRIL 10, 1984	1ST (LO-LEVEL)	-1.08×10^{-10}	-0.4×10^{-11}
	2ND (HI-LEVEL) (2 HRS. LATER)	-6.5×10^{-10}	-3.6×10^{-11}

NOTES: -DELTA f/f IS AT THE OUTPUT CONNECTOR OF THE M100 RUBIDIUM OSCILLATOR.

-M100 S/N 1492 PRODUCTION UNIT USED FOR TEST, 10 MHz OUTPUT, AT-CUT CRYSTAL FROM COLORADO CRYSTAL COMPANY.

GLASS RADIATION DATA [1]

Ball Efratom Division

Material	Manufacturer	Thickness (mil)	Radiation		Wave Length (μm)	Transmission Loss (percent)	Reference
			Fluence or Dose	Energy (MeV)			
0211 silica	Corning	6	2.7×10^{15} e/cm^2	1.2	WB	1.8	11-9
	Corning	26	2.7×10^{15} e/cm^2	1.2	WB	7.6	11-9
soda lime plate glass	Pittsburgh Plate Glass Co	250	1.7×10^{15} e/cm^2	1.2	WB	26	11-9
		-	10^{19} n/cm^2	fission	WB	0	-
Ge narrow band pass filter	OCLI	-	5×10^{17} e/cm^2	1	5-15	0	11-9
Ge lens	-	-	5×10^{17} e/cm^2	1	13-16	0	11-9
Ge filter A.R. coated	-	62.5	5×10^{17} e/cm^2	1	5-15	0	11-9
red cerium doped glass	Corning	80	8.5×10^{16} e/cm^2	1	0.8	24	11-9
		80	1.3×10^{17} e/cm^2	1	0.8	56	11-9
		160	1.5×10^{16} e/cm^2	1	0.8	14	11-9
		160	7×10^{16} e/cm^2	1	0.8	33	11-9
		160	1.6×10^{17} e/cm^2	1	0.8	58	11-9
SK14	Schott	80	8.2×10^{13} e/cm^2*	2.5	1	0	11-10
7070 (BS)	Corning	-	10^{15} n/cm^2	fission	WB	0	-
lead glass	-	-	10^{14} n/cm^2	fission	WB	0	-
GeO_2	-	-	10^7 rad	Co^{60}	WB	0	-
aluminosilicate (AS)	(CORNING 1720)	45	10^6	Co^{60}	0.79	3.1	-
borosilicate (2)(BS)	-	62 (3)	10^6	Co^{60}	0.79 (4)	2.6 (5)	-

(1) FROM:
TABLE 11-9 - SUMMARY OF RADIATION EFFECTS IN OPTICAL MATERIALS

FROM VOL. I, 2ND EDITION "PRINCIPLES AND TECHNIQUES OF RADIATION HARDENING," DR. NORM J. RUDIE,

WESTERN PERIODICALS CO. NORTH HOLLYWOOD, CAL.

(2) EFRATOM LAMPS AND CELLS ARE BOROSILICATES, CELL-CORNING #7740 (PYREX TRADE NAME) LAMP-SCHOTT 8400 SERIES

THIS TEST DATA ACTUALLY TAKEN USING EFRATOM CELL MATERIAL, IN 1974 (GPS)

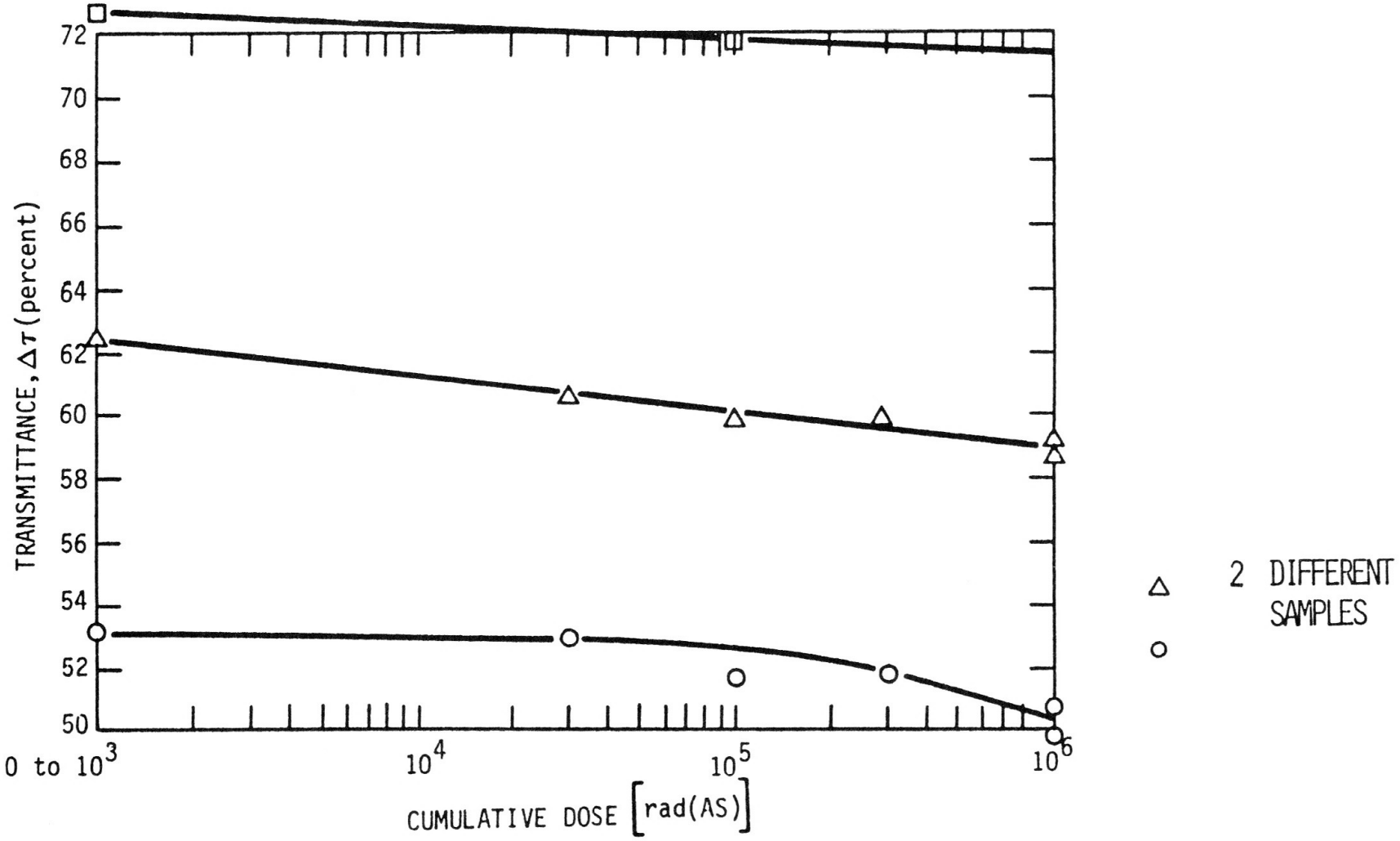
(3) EFRATOM LAMPS & CELLS 20 TO 30 MILS WALL THICKNESS

(4) EFRATOM LIGHT FREQUENCY AREA OF INTEREST 7800A AND 7947A

(5) EFRATOM MEASUREMENTS: ~10% TRANSMISSION LOSS EQUALS FEW PARTS IN 10^{11} $\Delta f/f$

GLASS RADIATION DATA (continued)

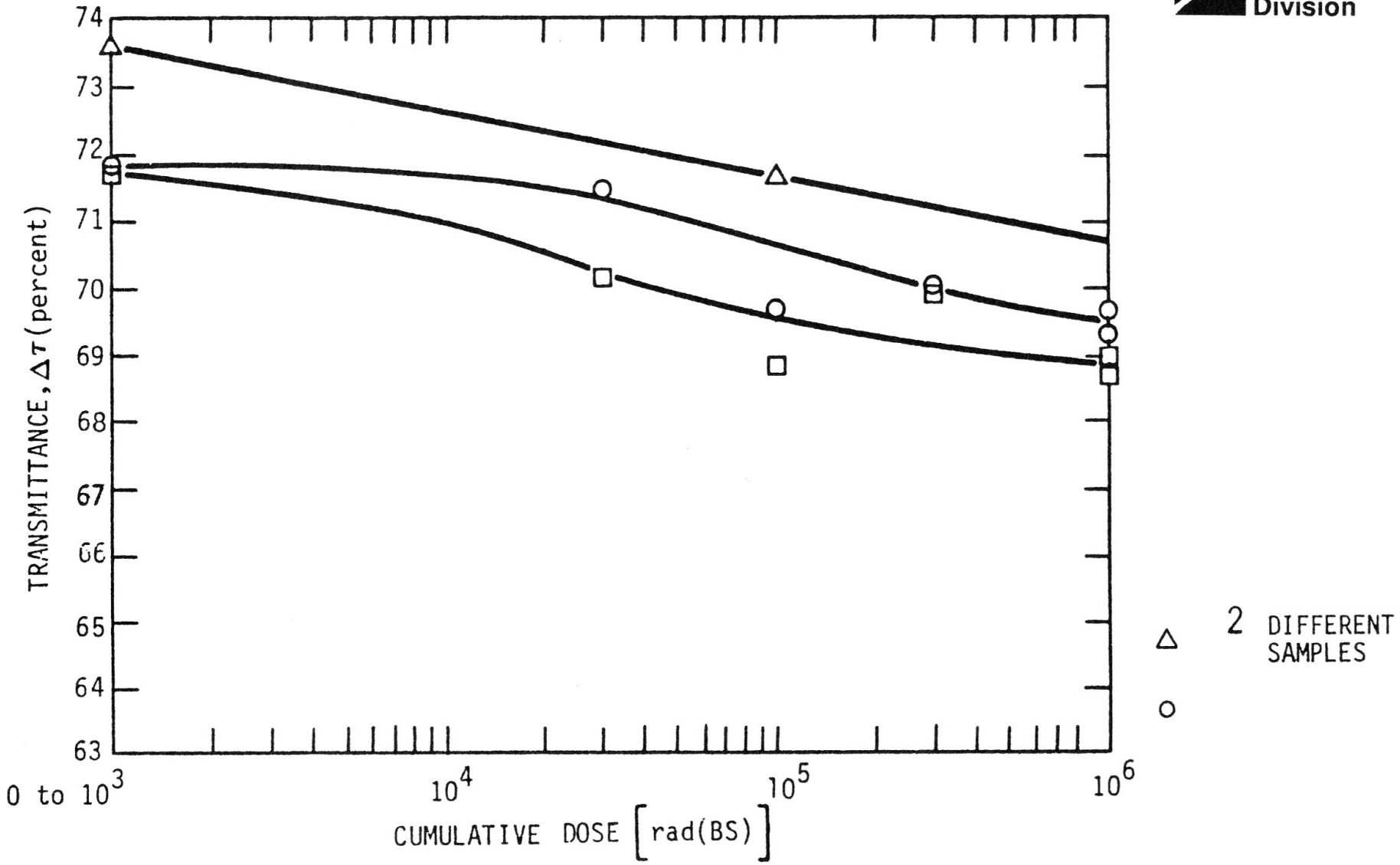
Ball Efratom Division



Transmittance of Aluminosilicate (AS) Corning 1720 as function of total integrated dose for 7800 A and 7947 A light. Samples were 0.114 cm thick. (Data taken by Rockwell.)

GLASS RADIATION DATA (continued)

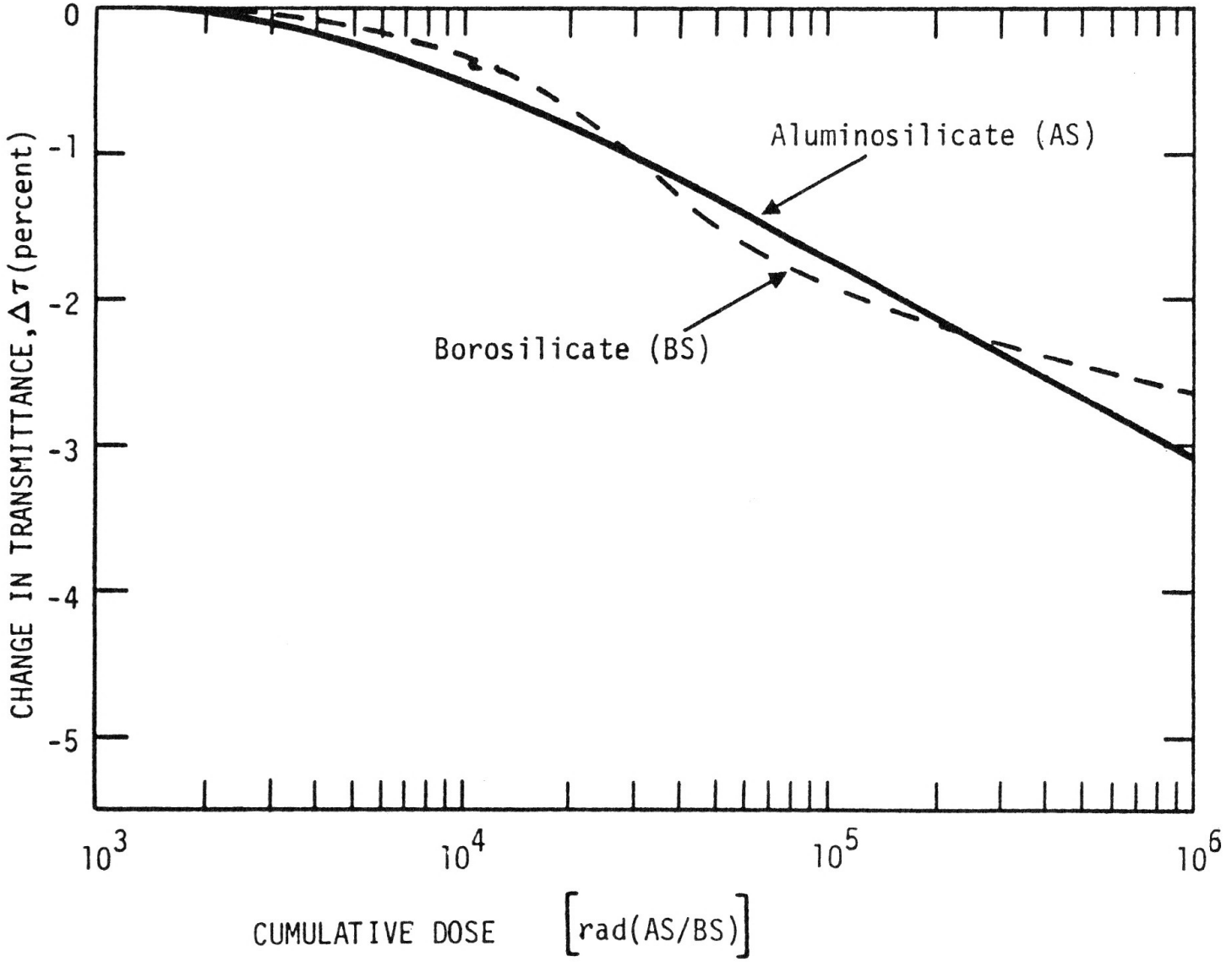
Ball Efratom Division



Transmittance of Borosilicate (BS) Corning 7070 as function of total integrated dose for 7800 Å and 7947 Å light. Samples were 0.157 cm thick. (Data taken by Rockwell.)

GLASS RADIATION DATA (continued)

Ball Efratom Division



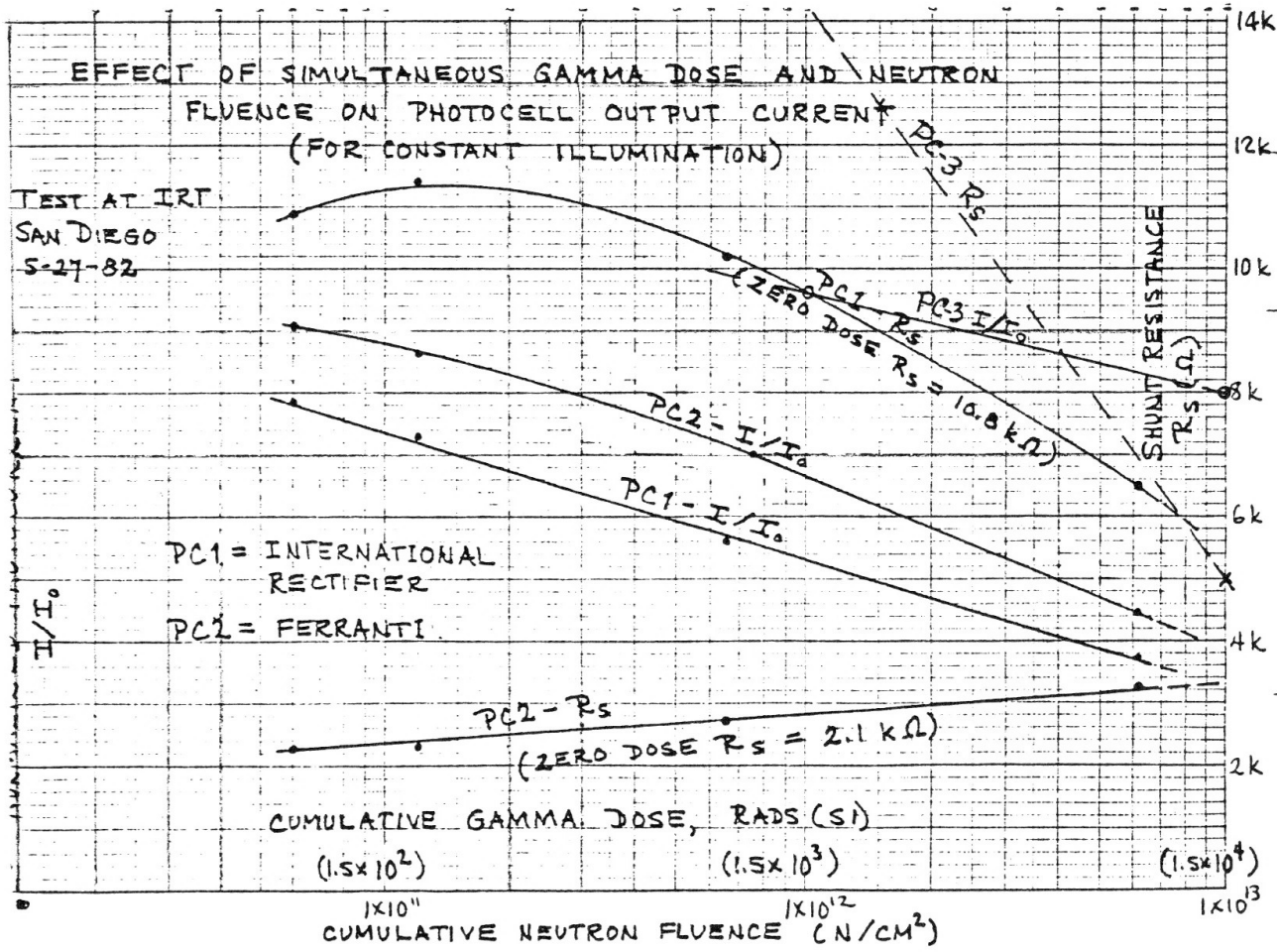
Nominal change in transmittance as function of total integrated dose for 7800 Å and 7947 Å light. (Data taken by Rockwell.)

PHOTOCELL IRRADIATION DATA

Ball Efratom Division

REV. C 9-88

- PHOTOCELL OUTPUT CURRENT (FOR CONSTANT LIGHT INTENSITY) SHOWS A SIGNIFICANT REDUCTION OF 60 TO 70% IN A NEUTRON FLUENCE ENVIRONMENT OF ~ 1×10^{13} N/CM^2.



UNIT TOLERANCE TO PHOTOCELL CURRENT REDUCTION LIES IN THE > 80% RANGE WITH THE PRESENT CIRCUIT GAINS.

— MINIMUM R_S FOR SATISFACTORY SHORT TERM STABILITY ~1 K GOOD MARGIN EXISTS TO ALLOW HIGHER RADIATION LEVEL.

— IF GREATER THAN 10^{13} N/CM^2 ENVIRONMENT IS NECESSARY, A HARDENED PHOTOCELL MAY BE AVAILABLE OR A SETTING CHANGE OF Rb RESONANCE SIGNAL AND PREAMP GAINS WILL ALSO INCREASE THE TOLERANCE TO PHOTOCELL DEGRADATION. IN ADDITION, A LIGHT LEVEL SENSE CIRCUIT CAN BE INCORPORATED WHICH AUTOMATICALLY CHANGES THE GAINS.

—EFFECT OF GAMMA RADIATION IS MINOR COMPARED TO THE NEUTRON ENVIRONMENT.

-PC-3 USED IN M-3000

Summary of Radiation Effects on Physics Package Components

Efratom Tests (1982) and Rockwell GPS Tests (1974)

Tests conducted by Efratom at IRT San Diego in May 1982, and Rockwell International Autonetics Radiation Lab in 1974, showed zero to a maximum of 3.1% transmission loss, when Efratom glass for lamps and cells was radiated. Glass included Schott 8400 series, and Corning 1720. Mylar and mica windows used in physics package were also tested.

SOURCE	RADIATION DOSE DOSE	GLASS TRANSMISSION LOSS	MYLAR & MICA TRANSMISSION LOSS
Co^{60} (RI, 1974)	GAMMAS 10^6 RADSS(Si)	Zero to 3.1%	Loss not detectable
2.5 MeV (RI, 1974)	8.2×10^{13} e/cm^2 [~1.6×10^6 RADS(Si)]	Loss not detectable	Loss not detectable
Fission (Efratom/ IRT, 1982)	7.5×10^{12} N/cm^2 Neutrons [~1.1×10^4 RADS(Si)]	Loss not detectable (<1%)	Loss not detectable (<1%)

CONCLUSIONS

- Rubidium physics package glass components are hard to combined total dose/neutron fluence and dose rate levels for the most stringent space and ground tactical environments.

- Efratom's M100, M3000 military rubidium oscillators have been exposed to various levels of combined total dose/neutron fluence and have operated satisfactorily.

- An M100 military unit operated satisfactorily in a combined environment of 11.5 KRADS (Si) and $1x10^{13}N/cm^2$. After being turned off and stored for 4 years, it was turned on again and operated like a normal production unit.

- An FRK Navstar GPS unit was turned on in 1991 after 13 years in orbital space storage and operated normally. The unit, during its storage life, accumulated at least 8 KRADS (Si) of total dose radiation.

Rb EMI SUMMARY

M100 EMI TEST SUMMARY

Ball Efratom Division

TEST	TEST RESULTS				REMARKS
	BROADBAND		NARROWBAND		
	PASS	FAIL	PASS	FAIL	
I. Conducted Interference					
A. CE01, .03 - 20 KHz, +28 Vdc			X		
B. CE01, .03 - 20 KHz, +28 Vdc RTN			X		
C. CE02, .03 - 20 KHz, Output J1			X		
D. CE03, .02 - 100 MHz, +28 Vdc	X				Spike on broadband graph is narrowband signal, therefore, narrowband limits apply.
E. CE03, .02-100 MHz, +28 Vdc RTN	X				Again, spikes on broadband graph are narrowband signals and narrowband limits apply.
F. CE04, .02 - 100 MHz, Output J1		X		X	Broadband exceeded limits by maximum of 6 dB at 4.6 MHz, 5 MHz, 3.1 MHz, 3.7 MHz; 10 MHz, 20 MHz, 30 MHz, 40 MHz are output signal and its associated harmonics.
II. Radiated Interference					
A. RE02, .014 - 1000 MHz		X		X	Broadband exceeded limit by 3 dB at 18 MHz and 24 MHz. Narrowband exceeded limit by 35 dB at 60 MHz; 25 dB at 70 MHz, 120 MHz; 15 dB at 10 MHz, 18 MHz, 24 MHz, 75 MHz, 180 MHz, 240 MHz; 10 dB or less at 40-50 MHz range, 215 MHz, 360 MHz, 420 MHz, 480 MHz, 720 MHz, 845 MHz.

M100 EMI TEST SUMMARY (Continued)

Ball Efratom Division

TEST	TEST RESULTS				REMARKS
	BROADBAND		NARROWBAND		
	PASS	FAIL	PASS	FAIL	
III. Susceptibility Testing					
A. CS01, .03 - 50 KHz					
1. +28 Vdc			X		
2. +28 Vdc RTN			X		
B. CS02, .05 - 400 MHz					
1. +28 Vdc				X	Failed from 233 MHz to 390 MHz
2. +28 Vdc RTN				X	Failed from 52 MHz to 246 MHz
C. CS06, Conducted Spike	X				
D. RS01, Magnetic Field, 30 Hz - 30 KHz			X		
E. RS02, Magnetic Induction					
F. RS03, Electric Field				X	Failed from 50 MHz to 260 MHz

UNDERSTANDING THE SPECS

FREQUENCY AND TIME

$$F = \frac{1}{T}$$

- Where F = frequency (= number of "events" per unit time)

  T = period (= time between "events")

- Accumulated Clock Time = $\frac{\text{Total Number of Events}}{\text{Number of Events Per Unit of Time}}$

- Frequency Standard + Counting Mechanism = Clock

- Examples of Frequency Standards: The Rotating Earth, Pendulum, Quartz Crystal Oscillator, Atomic Standards, etc..

- Cesium Atomic Oscillator - (^{133}Cs) Atomic Resonance = 9,192,631,770 Hz
  Units of Time = 1 second

Courtesy of John Vig, Army-LABCOM

DEFINITION OF TERMS AS APPLIED TO OSCILLATORS[1]

Aging (Implying Frequency Aging)

The change in frequency with time due to internal changes in the oscillator. It is the frequency change with time while factors external to the oscillator (environment, power supply, etc.) are kept constant. Generally, aging, rather than drift, is what one measures during oscillator evaluation.

Drift (Implying Frequency Drift)

The change in frequency with time that one observes in an application. Drift is due to aging plus changes in the environment and other factors external to the oscillator.

Accuracy (Of Output Frequency)

The degree of conformity of a measured or calculated value to some specified value or definition. In the case of time and frequency, the ultimate frequency accuracy is defined by the ^{133}Cs Atomic Resonance of 9,192,631,770 Hz.

Frequency Offset

The difference between the realized value and the nominal frequency value.

(1) Taken in part from letter by David W. Allan, NIST to CCIR Study Group XII U.S. Committee members 3-17-89.

DEFINITION OF TERMS AS APPLIED TO OSCILLATORS (CONT.)

Calibration

The process of identifying and measuring errors in instruments and/or oscillators. In a frequency generator, calibration is generally related to identifying and eliminating a frequency change due to aging and/or drift.

Frequency Instability (Stability)

It is expressed by the frequency change within a given time interval τ. Generally, it distinguishes between systematic effects such as frequency drift and stochastic frequency fluctuations. Special variances have been developed for the characterization of these fluctuations (i.e. Allan Variance). Systematic instabilities may be caused by radiation, vibration, pressure, temperature, humidity, etc. In many contexts the expression "stability" instead of "instability" is used and is acceptable.

Retrace Frequency

With respect to a frequency generator, retrace generally refers to the frequency change from one turn-on to the next, (i.e., how well it goes back to its original frequency after it has been off for a while and turned back on). It is the frequency error or hysteresis from its frequency value before the last turn off.

WHY "ALLAN VARIANCE" ?

- Classical Variance, $\sigma^2 = \frac{1}{m-1} \sum_{i=1}^{m} (y_i - \bar{y})^2$, diverges for commonly observed noise processes, such as random walk, i.e., the variance increases with increasing number of data points.

- Allan Variance:

  - Converges for all noise processes observed in precision oscillators.

  - Has straightforward relationship to power law spectral density types.

  - Is easy to compute.

  - Is faster and more accurate in estimating noise processes than the Fast Fourier Transform.

Courtesty of John Vig, Army-LACOM

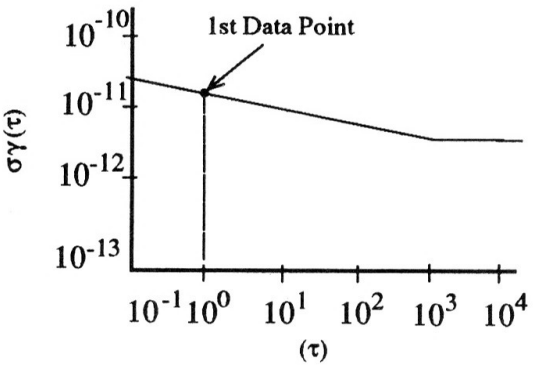
WHAT IS "ALLAN VARIANCE"?

- A proven way to characterize the stability of a precision oscillator

A sample calculation of Allan Variance, $\sigma_y^2(\tau)$

$$\sigma_y^2(\tau) = \frac{1}{2(m-1)} \sum_{k=1}^{m-1} (\bar{y}_{k+1} - \bar{y}_k)^2$$

In the example below:
Number of data values available, m=9
Number of differences averaged, m-1=8
Sampling time interval τ=1s



Data Values (y)	First Differences $(\bar{y}_{k+1} - \bar{y}_k)$	First Differences Squared $(\bar{y}_{k+1} - \bar{y}_k)^2$
892		
809	-83	6889
823	14	196
798	-25	625
671	-127	16129
644	-27	729
883	239	57121
903	20	400
677	-226	51076

$$\sum_{k=1}^{m-1} (\bar{y}_{k+1} - \bar{y}_k)^2 = 133165$$

Based on these data:

$$\sigma_y^2(\tau) = \frac{133165}{2(8)} = 8322.81$$

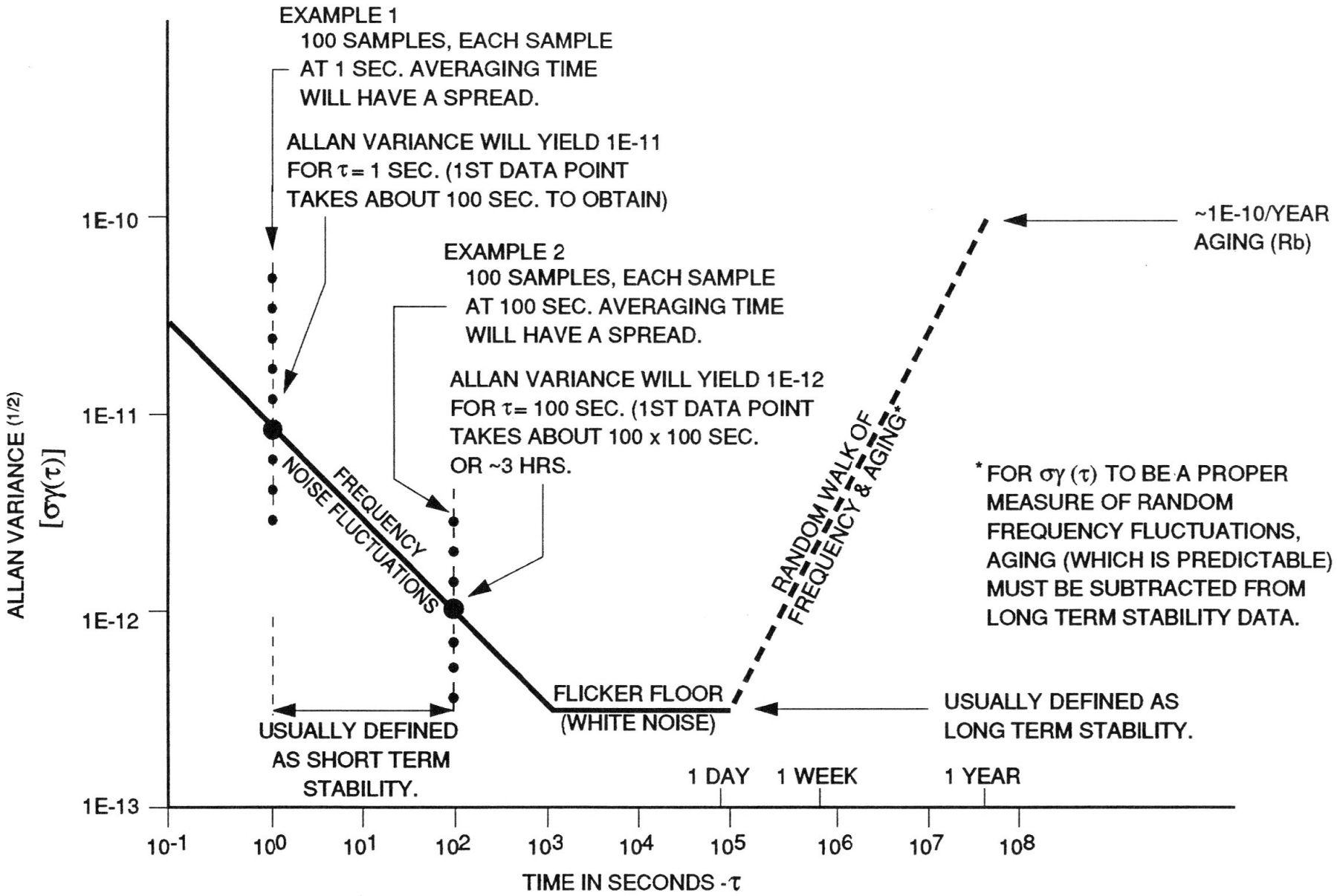
$$[\sigma_y^2(\tau)]^{1/2} = \sqrt{8322.81}$$

$$\sigma_y(\tau) = 91.23, \ \tau=1s$$

In this example, the data values are parts in 10^{13}.

TIME DOMAIN STABILITY

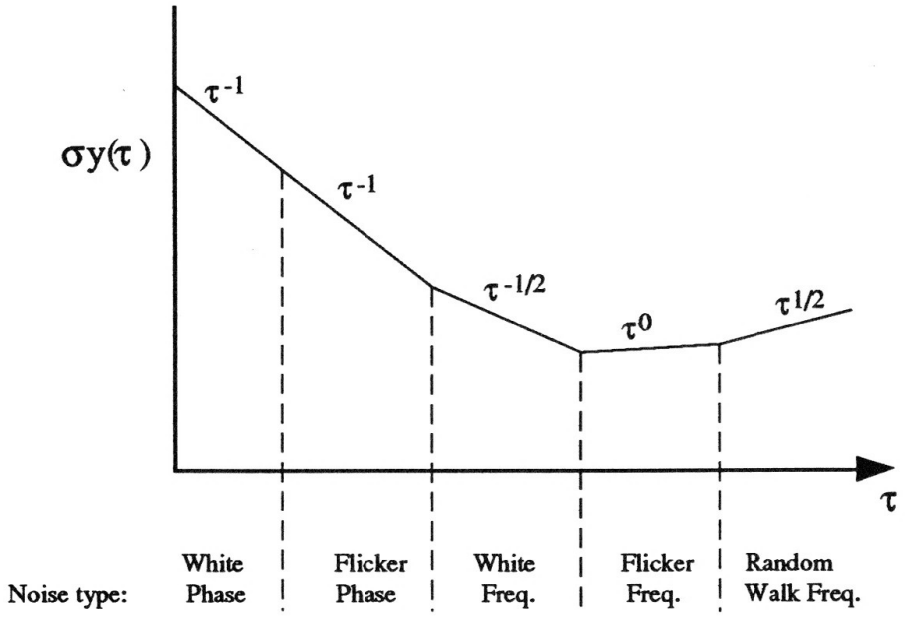
Ball Efratom Division



12/91

POWER LAW DEPENDENCE OF σy(τ)

Ball Efratom Division



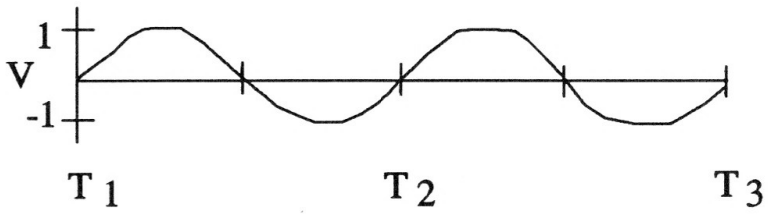
Below the flicker of frequency noise (i.e., the "flicker floor") region, crystal oscillators typically show τ^{-1} (white phase noise) dependence. Atomic standards show $\tau^{-1/2}$ (white frequency noise) dependence down to about the servo-loop time constant, and τ^{-1} dependence at less than that time constant. Typical τ at the start of flicker floors are: 1 second for a crystal oscillator, 10^3 s for a Rb standard and 10^5 s for a Cs standard.

Courtesy of John Vig, Army-LABCOM

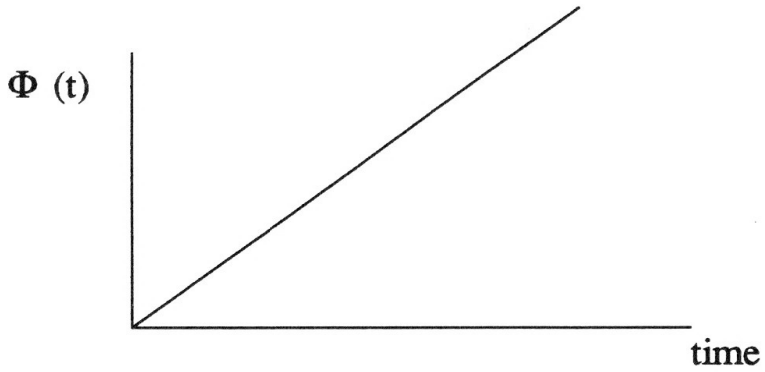
SHORT-TERM INSTABILITY (STABILITY)

Ball Efratom Division

STABLE FREQUENCY (Ideal oscillator)

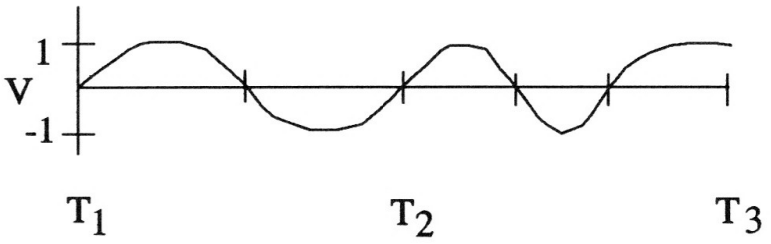


$$V(t) = V_o \sin(2\pi V_o t)$$

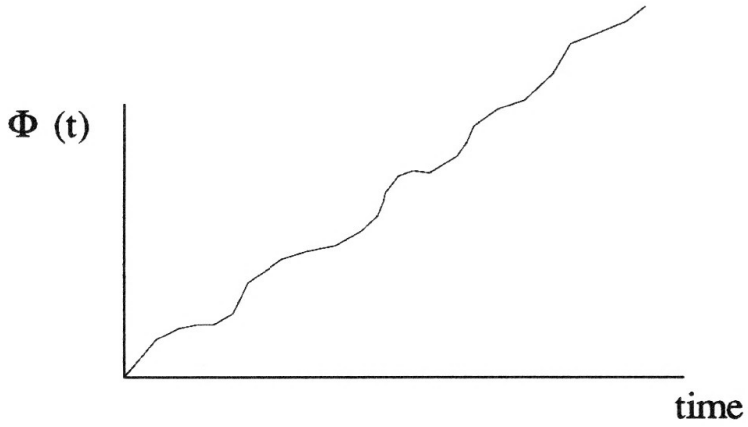


$$\Phi(t) = 2\pi V_o t$$

UNSTABLE FREQUENCY (Real oscillator)



$$V(t) = [V_o + \varepsilon(t)] \sin[2\pi V_o t + \Phi(t)]$$



$$\Phi(t) = 2\pi V_o t + \Phi(t)$$

= Instantaneous phase

WHERE

- $V(t)$ = Oscillator Output Voltage
- V_o = Nominal Peak Voltage Amplitude
- $\varepsilon(t)$ = Amplitude Noise
- V_o = Nominal (or "carrier") Frequency
- $\Phi(t)$ = Deviation of Phase from Nominal

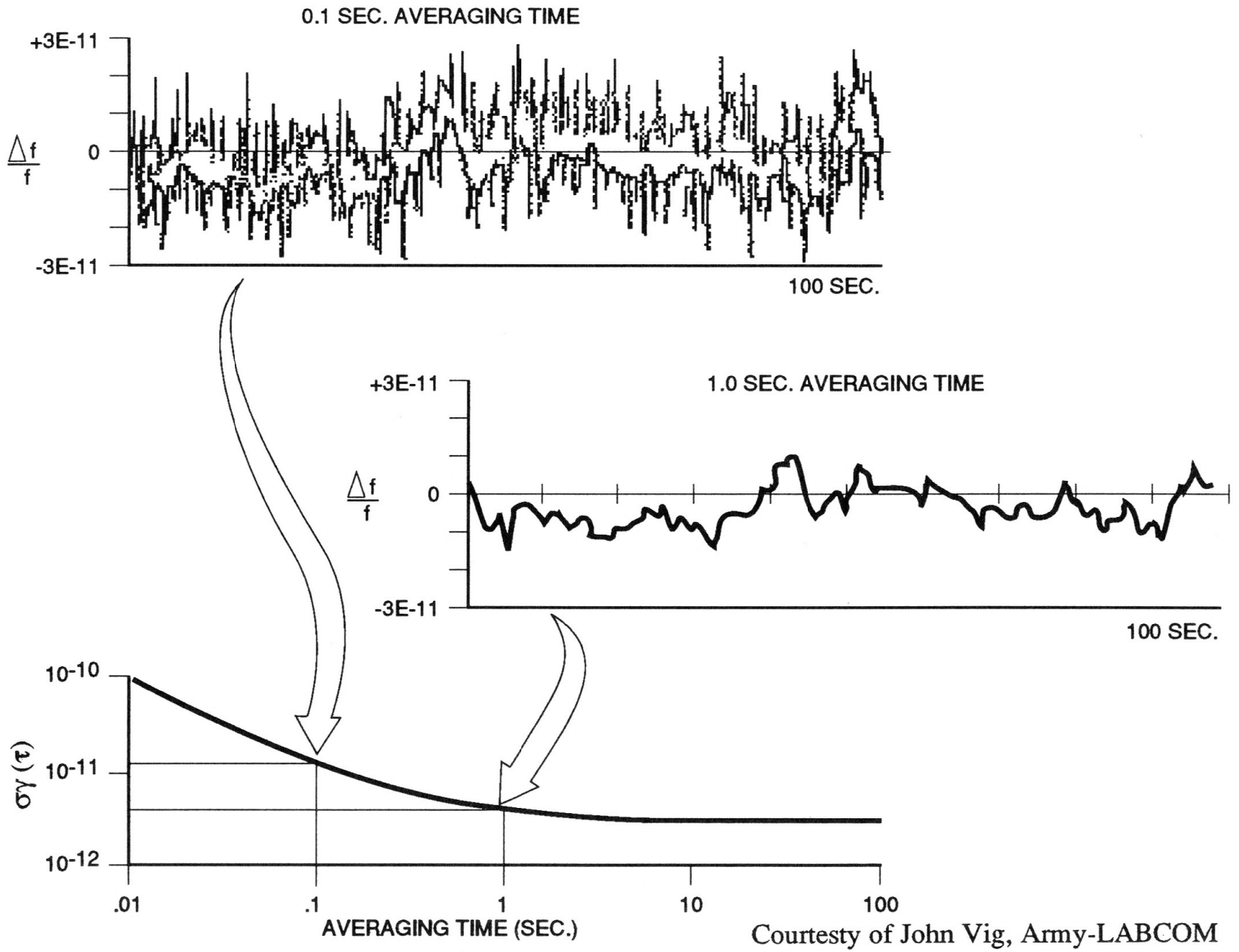
$$\text{Instantaneous Frequency, } V(t) \equiv \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = V_o + \frac{1}{2\pi}\frac{d\Phi(t)}{dt}$$

Courtesty of John Vig, Army-LABCOM

12/91

FREQUENCY NOISE AND ALLAN VARIANCE

Ball Efratom Division

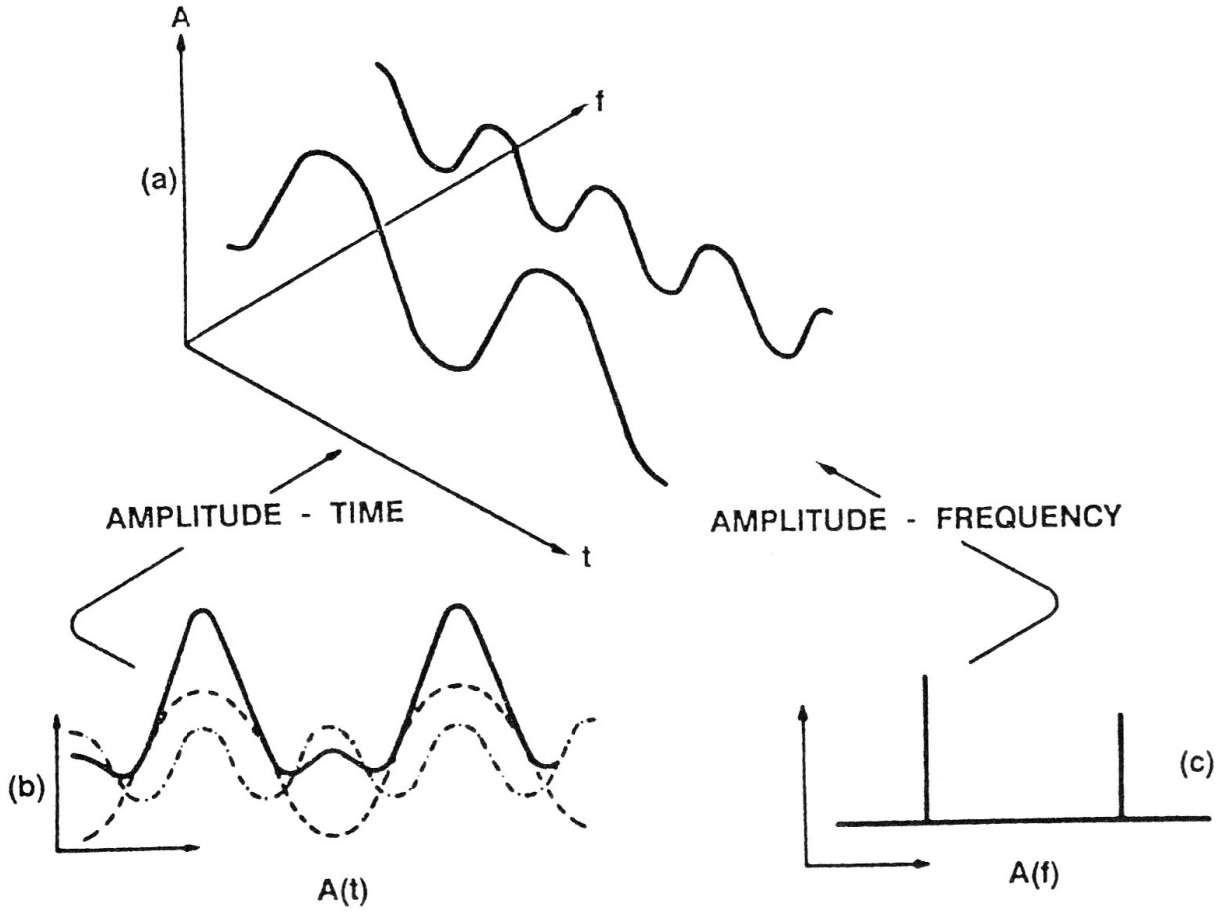


12/91

Courtesy of John Vig, Army-LABCOM

TIME DOMAIN vs. FREQUENCY DOMAIN

Ball Efratom Division



Example (a) shows a sine wave and its second harmonic. A signal consisting of the sum of the two waves is shown in the time domain (b), and in the frequency domain (c). In the time domain, all frequency components of a signal are summed together. In the frequency domain, signals are separated into their frequency components and the power level at each frequency is displayed.

7.11

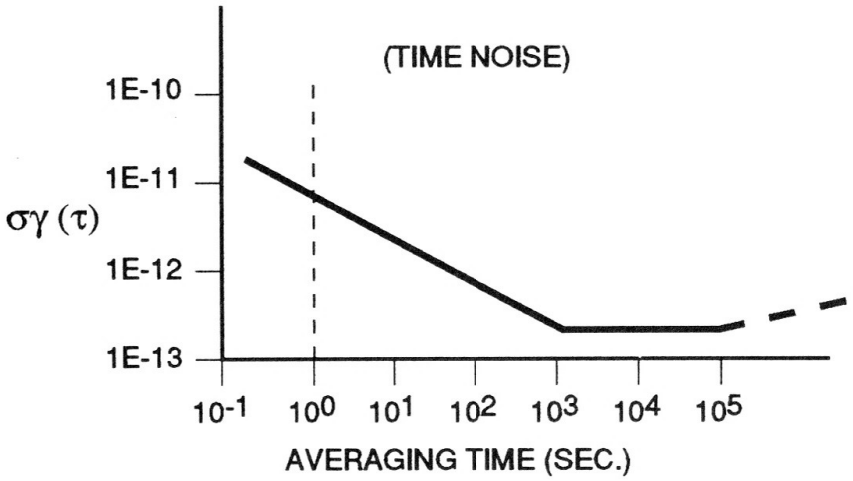
Courtesy of John Vig, Army-LABCOM

12/91

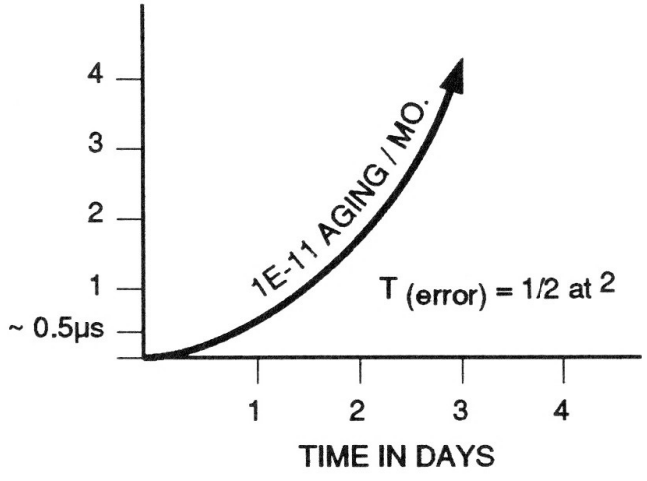
TIME & FREQUENCY DOMAIN & TIME ERROR

Efratom Division

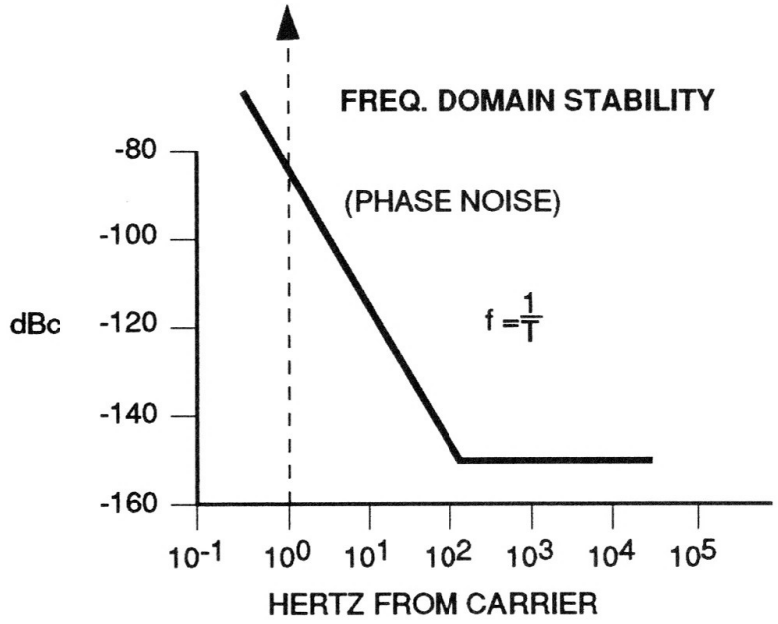
TIME DOMAIN STABILITY



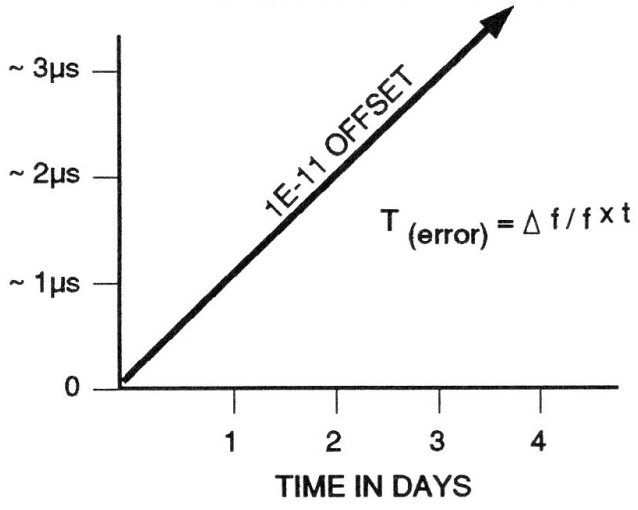
FREQ. AGING VS. TIME ERROR



FREQ. DOMAIN STABILITY

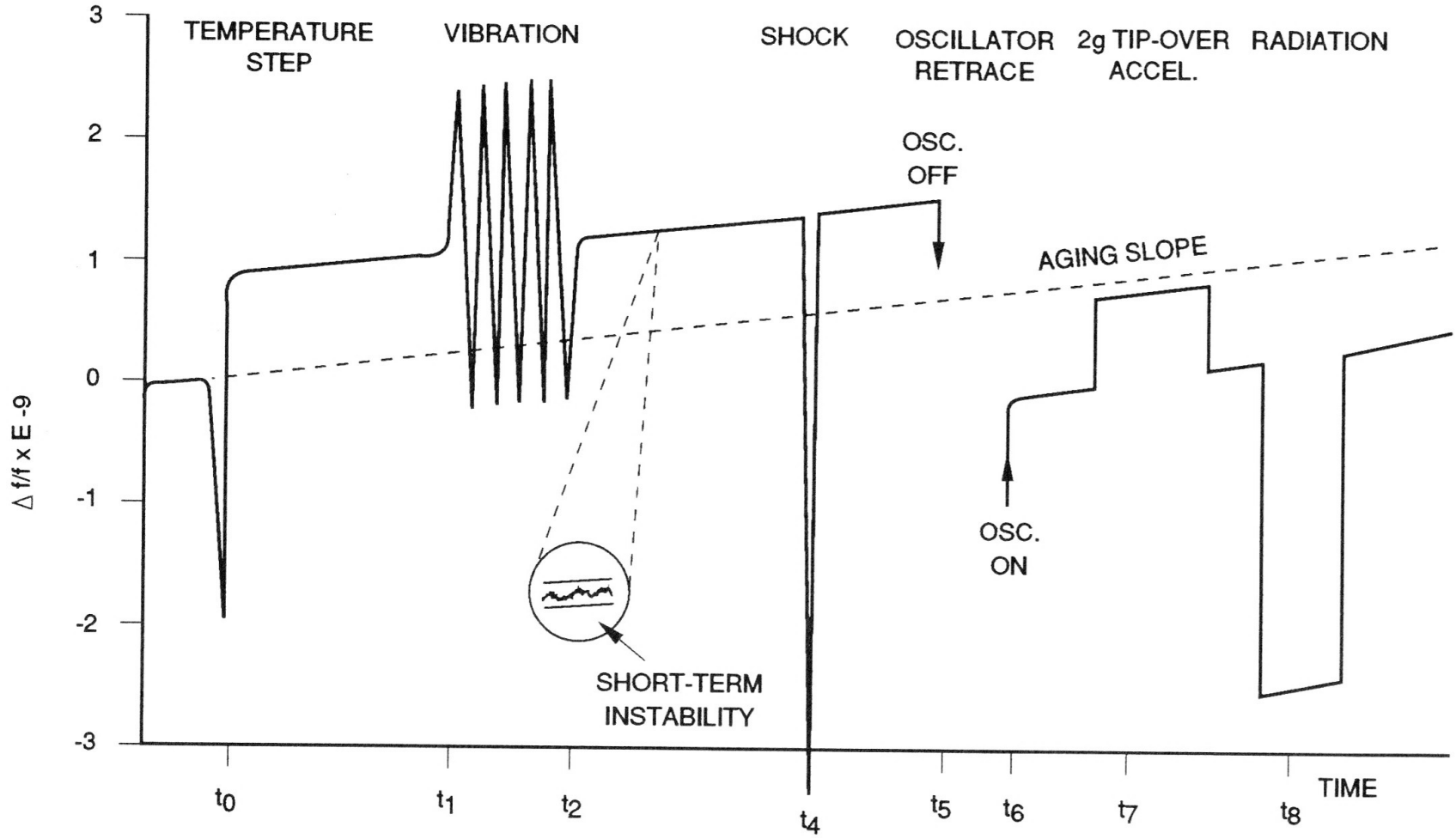


FREQ. OFFSET VS. TIME ERROR



TYPICAL BEHAVIOR OF QUARTZ CRYSTAL OSCILLATORS DUE TO ENVIRONMENTAL INFLUENCES

Ball Efratom Division



Courtesy of John Vig, Army-LABCOM

VIBRATION-INDUCED ALLAN VARIANCE DEGRADATION

Ball Efratom Division

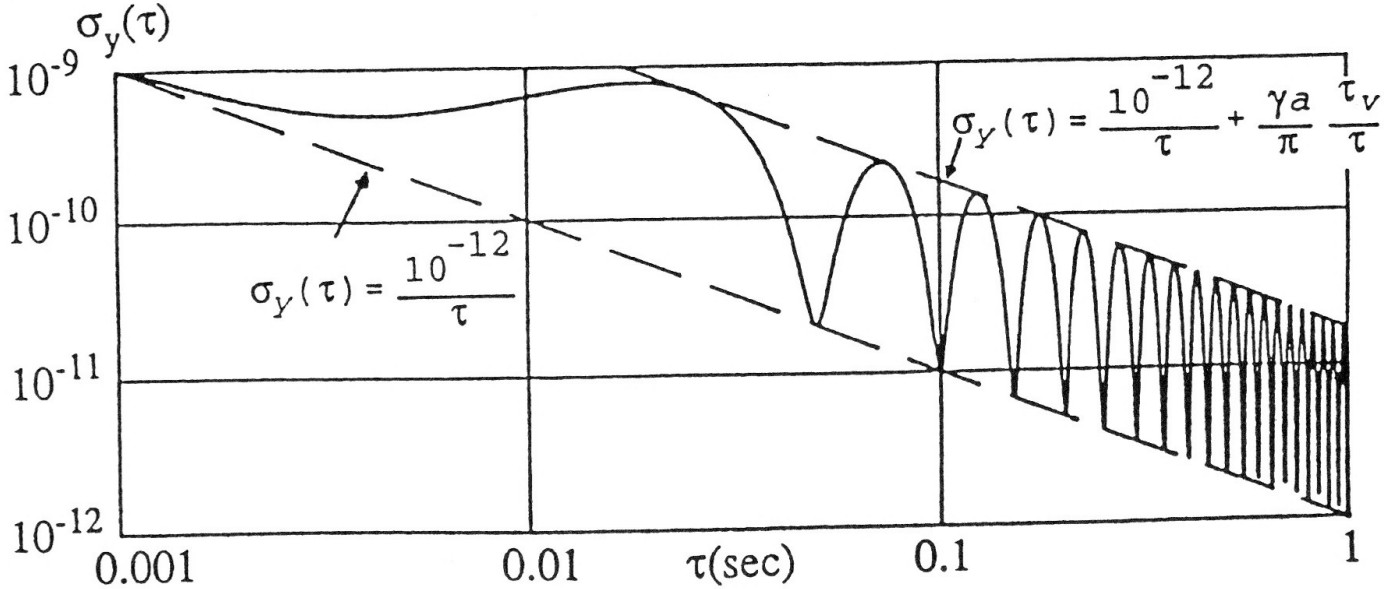
Vibration modulates the frequency and, thereby, degrades the short-term stability. The typical degradation due to sinusoidal vibration varies with averaging time, as shown. Since a full sine wave averages to zero, the degradation is zero for averaging times that are integer multiples of the period of vibration. The peaks occur at averaging times that are odd multiples of half the period of vibration. The $\sigma_y(\tau)$ due to a single-frequency vibration is:

$$\sigma_y(\tau) = \frac{\Gamma \cdot a}{\pi} \frac{\tau_v}{\tau} \sin^2\left(\pi \frac{\tau}{\tau_v}\right),$$

where τ_v is the period of vibration, τ is the measurement averaging time, Γ is the acceleration sensitivity vector, and **a** is the acceleration.

Example:

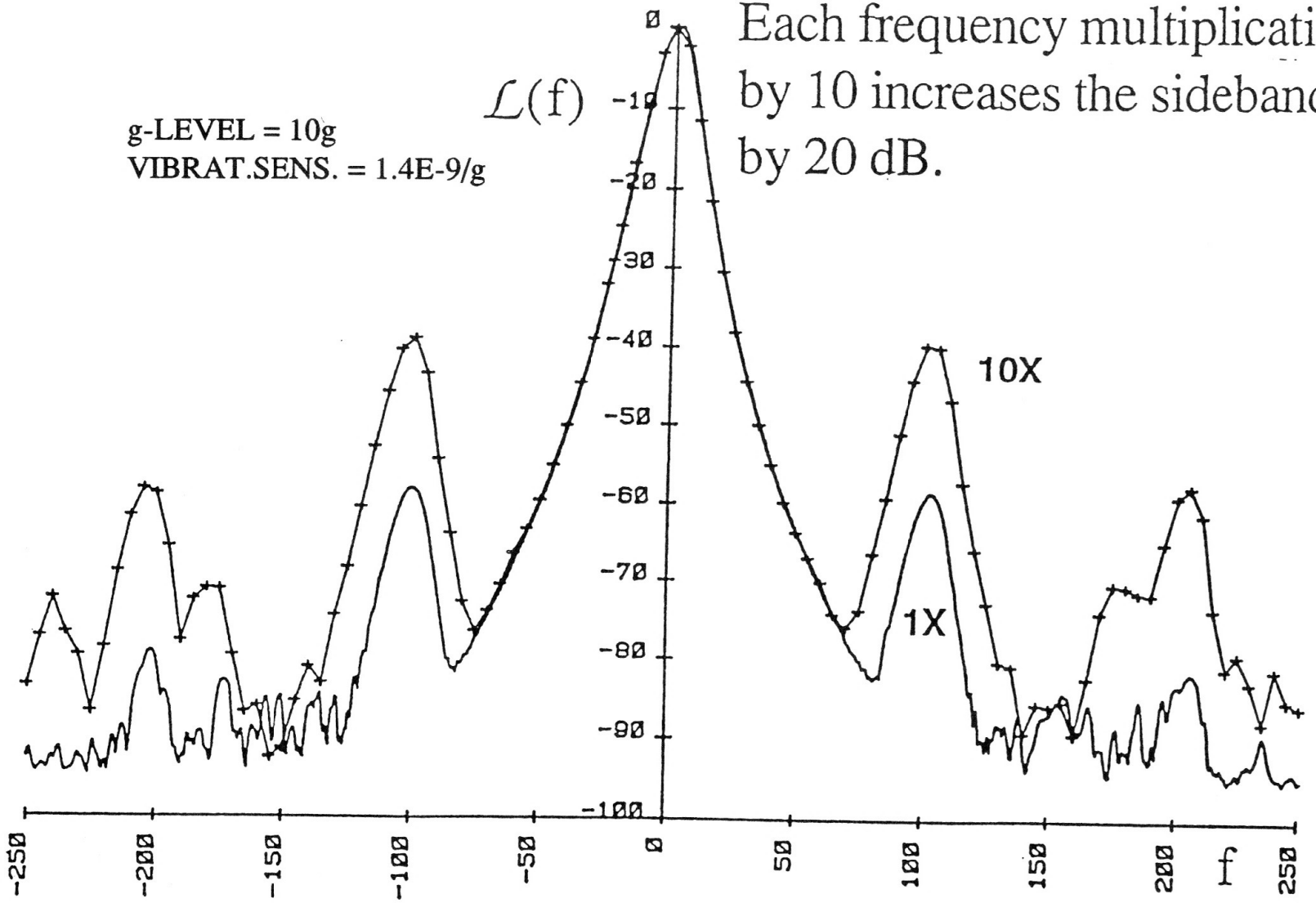
f_v = 20 Hz
a = 1.0 g along Γ
$|\Gamma| = 1 \times 10^{-9}/g$



Courtesy of John Vig, Army-LABCOM

VIBRATION-INDUCED SIDEBANDS

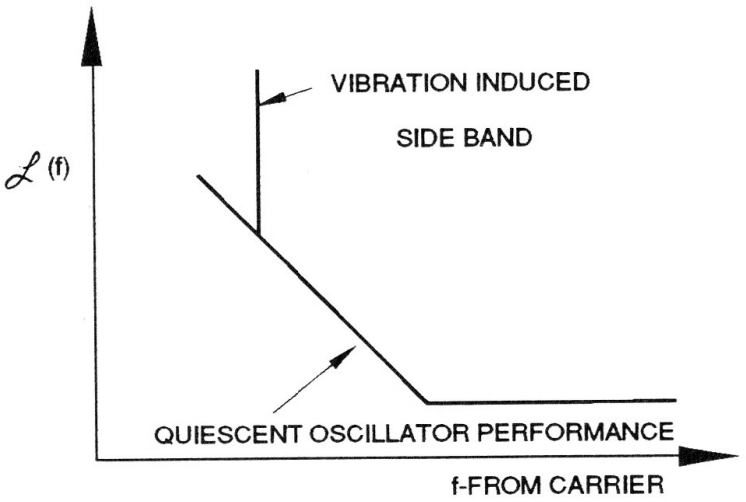
Ball Efratom Division

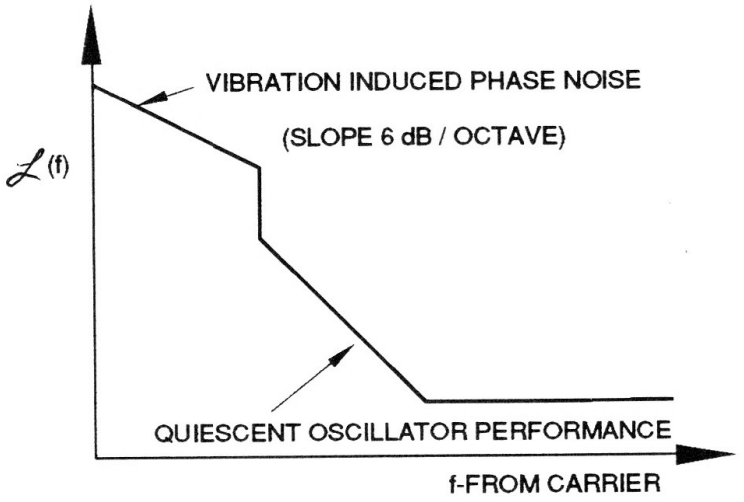


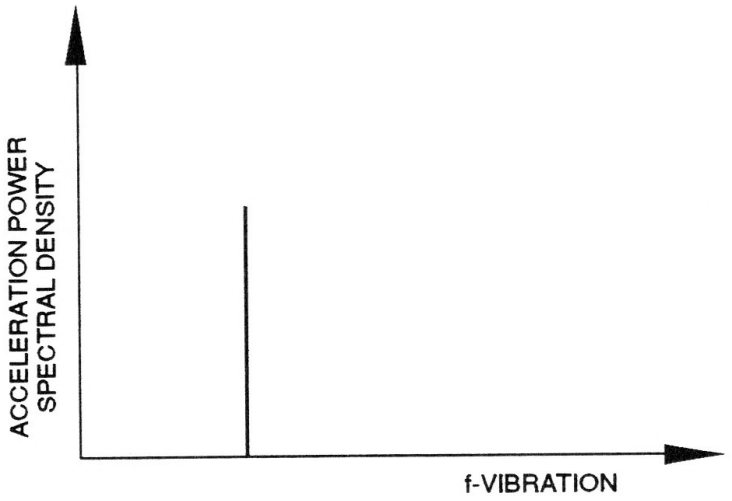
Courtesy of John Vig, Army-LABCOM

PHASE NOISE UNDER VIBRATION

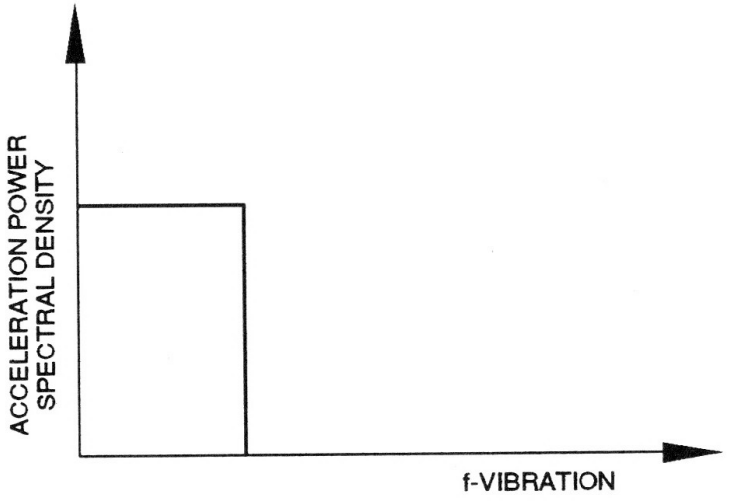
Ball Efratom Division







SINUSOIDAL VIBRATION



RANDOM VIBRATION

SINE VIBRATION-INDUCED PHASE NOISE

Ball Efratom Division

Sinusoidal vibration produces sidebands at $\pm f_v$ from the carrier, where f_v is the vibration frequency.

$$L'(f_v) = 20 \log \left[\frac{\overline{\Gamma} \cdot \overline{Af_o}}{2f_v} \right]$$

e.g., if $|\overline{\Gamma}|$=1 x 10^{-9}/g and f_o = 10 MHz, then even if the oscillator is completely **noise free at rest**, the phase "noise" due solely to a sine vibration level of 1g will be:

Vibr. freq., f_v, in Hz	$L'(f_v)$, in dBc
1	-46
10	-66
100	-86
1,000	-106
10,000	-126

Courtesy of John Vig, Army-LABCOM

RANDOM VIBRATION-INDUCED PHASE NOISE

Random vibration's contribution to phase noise is given by:

$$L'(f) = 20 \log \frac{\Gamma \bullet A f_o}{2f}, \text{ where } |\overline{A}| = [(2)(PSD^*)]^{1/2}$$

e.g., if $|\overline{\Gamma}| = 1 \times 10^{-9}/g$ and $f_o = 10$ MHz, then even if the oscillator is completely **noise free at rest**, the phase "noise" due solely to a vibration PSD = $0.1 g^2/Hz$ will be:

Offset freq., f, in Hz	L′(f), in dBc/Hz
1	-53
10	-73
100	-93
1,000	-113
10,000	-133

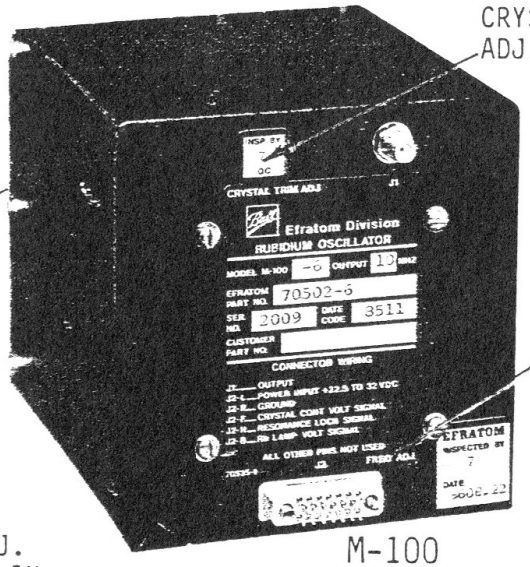
*Note: PSD=Power Spectral Density

Courtesy of John Vig, Army-LABCOM

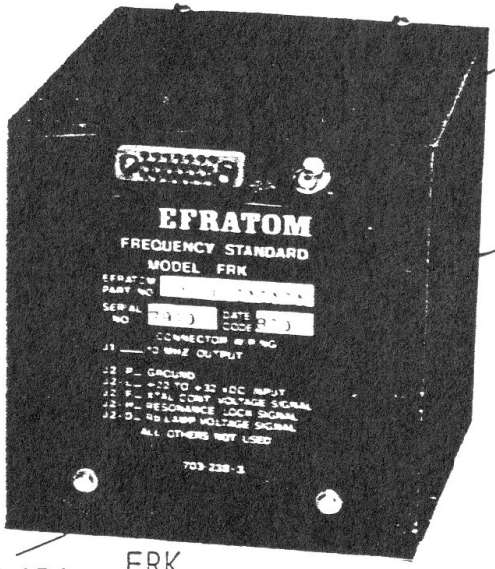
CALIBRATION NOTES

EFRATOM Rb OSCILLATOR CALIBRATION PORTS

Ball Efratom Division

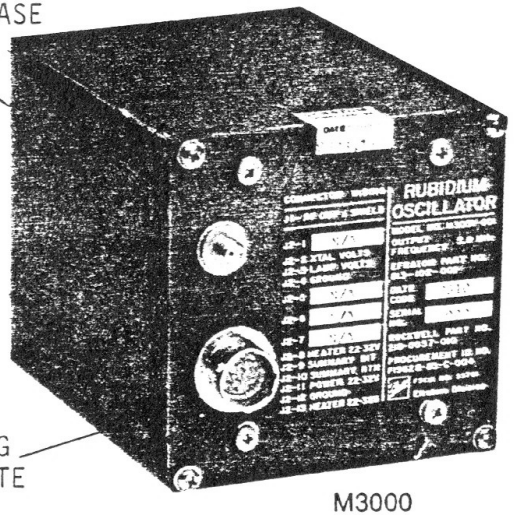


M-100



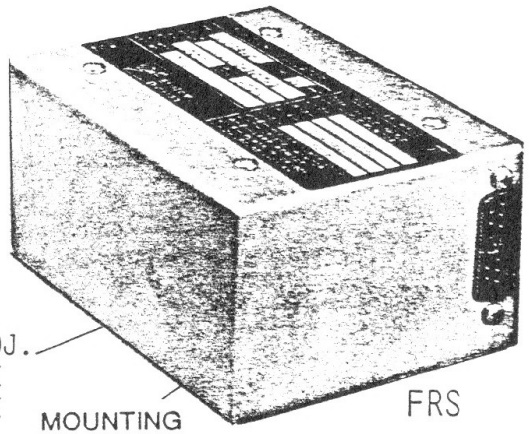
CRYSTAL ADJ. ON SIDE OF CASE

FRK



M3000

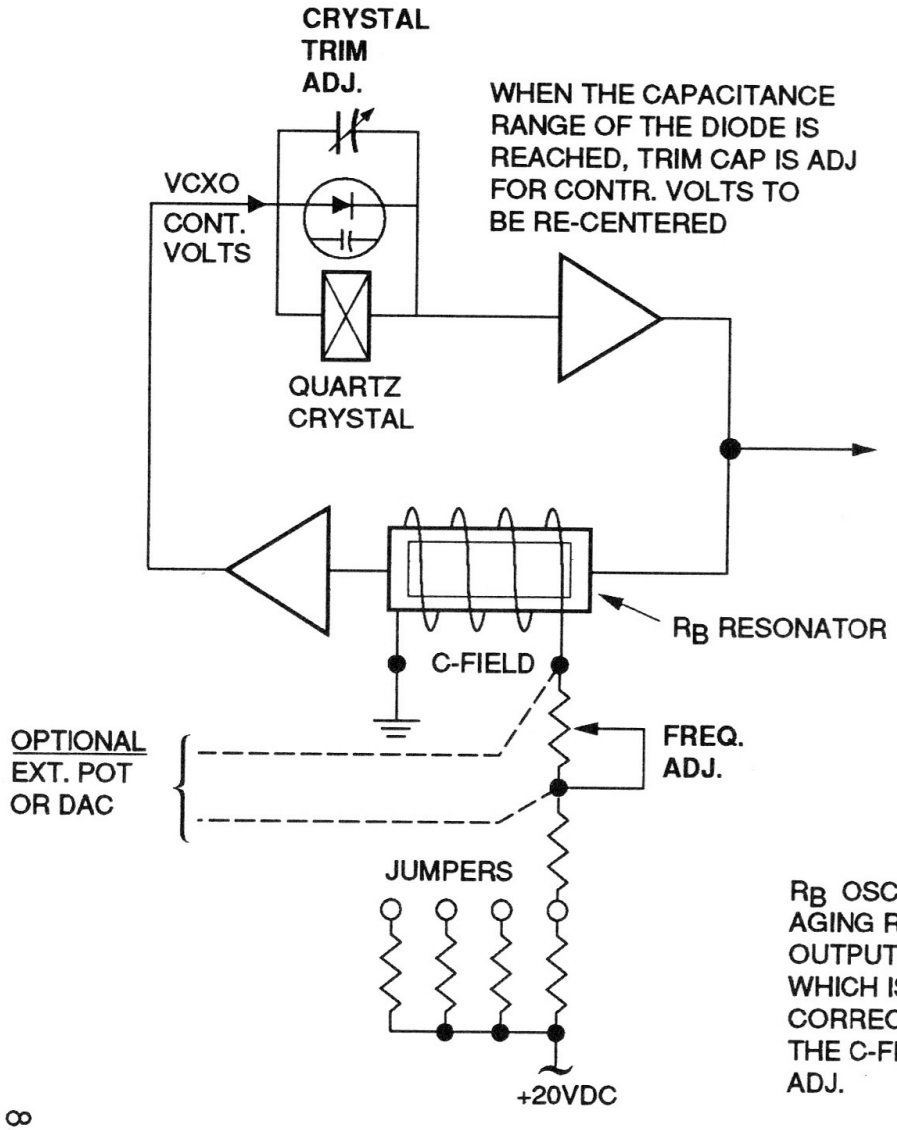
NOTE: FRS & M3000 DO NOT HAVE AN EXTERNAL CRYSTAL ADJ. CAPABILITY

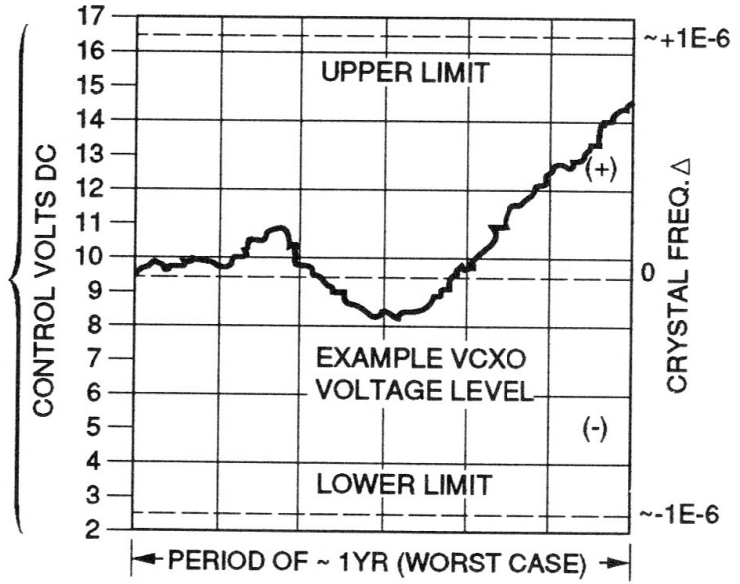


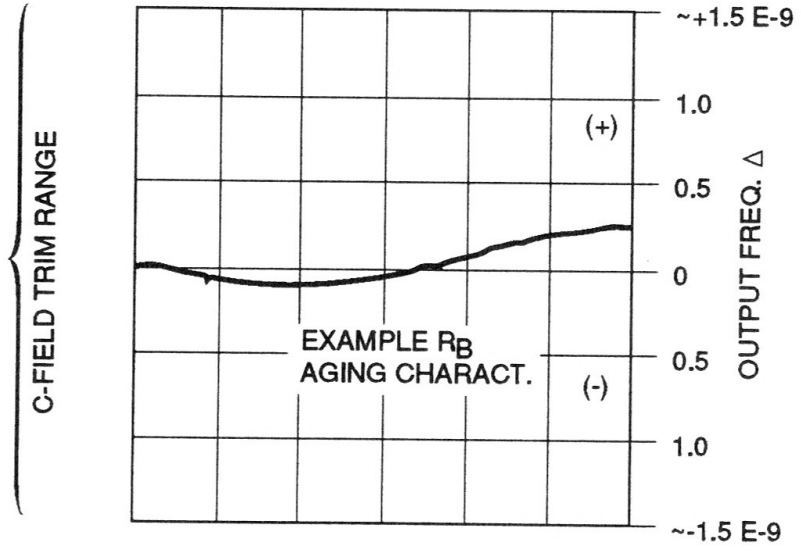
FRS

VCXO & C-FIELD ADJ. EXPLANATIONS FOR EFRATOM Rb OSCILLATORS

Ball Efratom Division





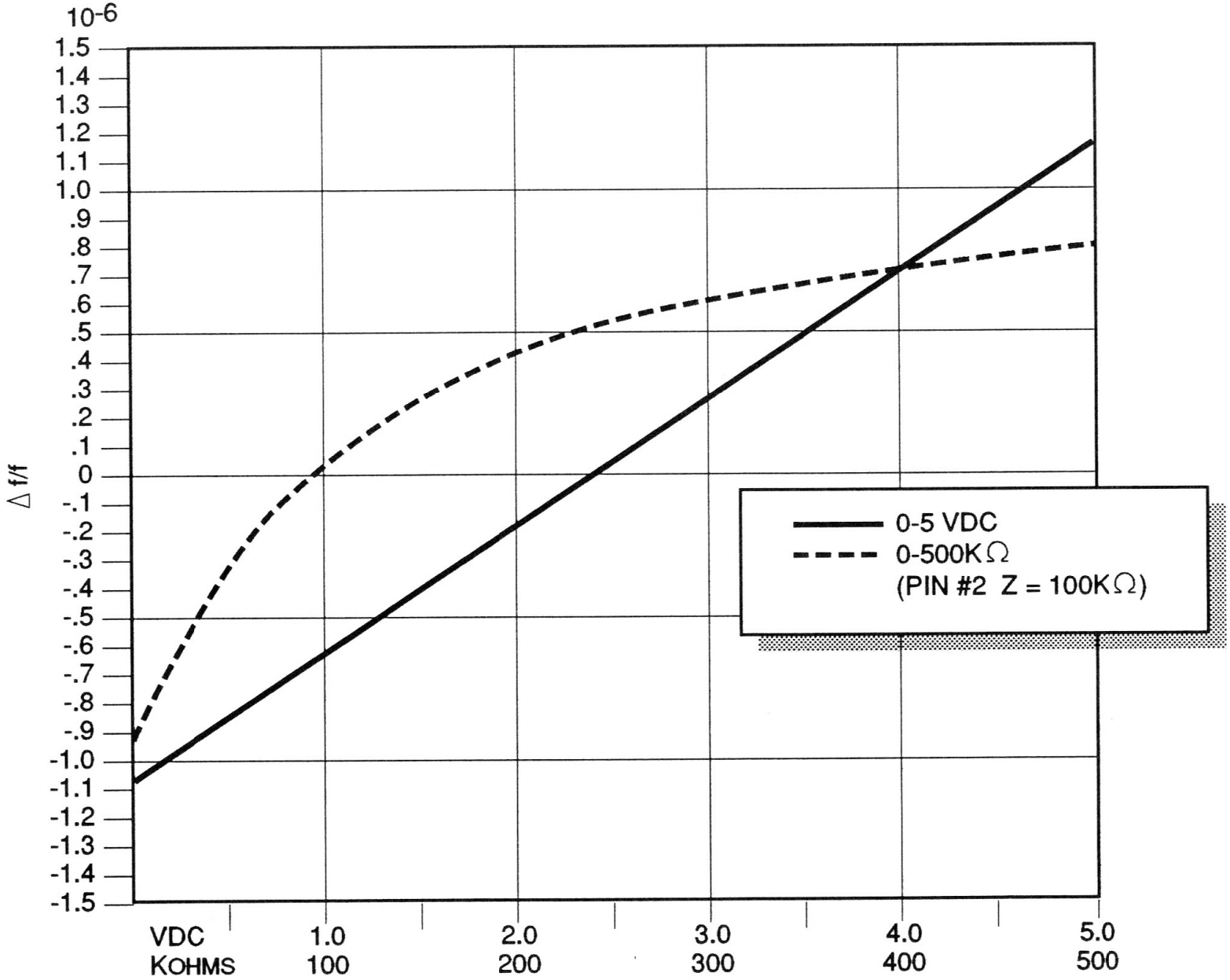


R_B OSCILLATOR AGING RESULT IN UNIT OUTPUT FREQ. Δ WHICH IS CORRECTED BY THE C-FIELD ADJ.

8.3

EMXO/ECXO QUARTZ CRYSTAL OSC.
FREQ. ADJUSTMENT AT EFC PIN

Ball Efratom Division



OMEGA/VLF NAVIGATION Rb CALIBRATION

TIME BETWEEN CALIBRATION OF ON-BOARD Rb OSCILLATOR TO MEET MAXIMUM NAVIGATIONAL ERROR ALLOWABLE

ΔX T (convert to seconds)

Allowable Error = 1 mile/4 hours flight time

$$\text{Time Error (Due To Clock) } \Delta t = \frac{\Delta X \text{ (Distance Error)}}{C \text{ (Speed of Light)}}$$

$$\Delta t \simeq 5.37\ \mu s$$

$$\text{Allowable Frequency Offset } = \Delta f/f = \frac{\Delta t}{T} \simeq 3.73\text{E-}10$$

$$\text{Time Between Calibration} = \frac{\text{Allowable offset}}{\text{Actual Offset as Function of Time}}$$

Actual Offset = Calibration Accuracy (1E-11)	0.1E-10
+Offset due to Environment (~ 1.6E-10)	1.6E-10
+Offset due to Frequency Aging (< 2E-10/year)	2.0E-10
Total ~	3.7E-10

$$\text{Time Between Calibration} = \frac{3.73\text{E-}10}{\sim 3.7\text{E-}10} \simeq 1 \text{ year}$$

$C \simeq 186 \times 10^3$ miles/sec
$(300 \times 10^6$ meters/sec)

8

CALCULATIONS FOR Δ TIME & FREQUENCY

GENERAL

Most systems using precision oscillators specify the allowable relative frequency deviation (Δf/f) or allowable accumulated time error (ΔT) of the reference oscillator or time base.

As a function of time, the oscillator frequency can be expressed as follows:

$$f_T = f_o + Df_rT$$

Where f_T = Frequency at Time T
f_o = Initial Frequency at Time T=0
f_r = Reference Frequency
D = Aging Rate

From the derivation of equation above, we obtain:

$$\Delta T = T_o + \left(\frac{f_o}{f} - 1\right)T + \frac{DT^2}{2}$$

Where ΔT = Accumulate Time Error
T_o = Initial Time or Sync Error
$\left(\frac{f_o}{f} - 1\right)$ = Relative Frequency Offset
D = Aging Rate
T = Elapsed Time

CALCULATION EXAMPLE FOR ΔT & TIME-BETWEEN-CALIBRATION (TBC)

Example 1

A spread spectrum communication system must maintain a 15 μs or less time error on a 4 hour mission.

The system uses a 10 MHz Rb oscillator with a 1E-11/month frequency aging, also the overall operating environment causes an averaged frequency offset of 5E-10. Consider the initial synchronization error to be negligible (ie: T_o=0)

ΔT Calculation

$$\Delta T_{Rb} = T_o + \left(\frac{f_o}{f_r} - 1\right) T + \frac{DT^2}{2}$$

$$= 0 + (5E\text{-}10)\ (4\ hrs^*) + (1/2)\ (1E\text{-}11/month^*)\ (4\ hrs^*)^2$$

$$= 72E\text{-}7\ sec + 40.32E\text{-}11\ sec$$

$$\Delta T_{Rb} = 7.2\ \mu s$$

(*Convert to seconds)

8

As can be seen from the above, the time error over a 4 hour period caused by aging is negligible in comparision to the time error caused by environmental effects on frequency.

ΔT AND TBC CALCULATIONS

Example 1 (continued)

TBC Calulation

$$TBC_{Rb} = \left(\frac{f_T}{fr} - 1\right)\left(\frac{1}{D}\right) \qquad \text{Where } \left(\frac{f_T}{fr} - 1\right) = \frac{\Delta t}{T}$$

$$TBC_{Rb} = \frac{\Delta t}{T}\left(\frac{1}{D}\right) = \frac{15\ \mu s - 7.2\ \mu s}{4\ hrs^*}\left(\frac{1}{D}\right) = 5.4E\text{-}10\left(\frac{1}{D}\right)$$

$$TBC_{Rb} = \frac{5.4E\text{-}10}{1E\text{-}11/mo.^*} = 54\ month$$

(*Convert to seconds)

ΔT AND TBC CALCULATIONS

Example 2

A 900 MHz Trunked Simulcast Communications System shall maintain its frequency to within ±1 Hz. What is the Time-Between-Calibration (TBC) for:

(A) 10 MHz Rb Oscillator with an aging rate of 1E-11/month

(B) 10 MHz Rb Precision Crystal Oscillator with an aging rate of 5E-10/day

Initial frequency offset due to setting accuracy and environmental effects (Temp, Barometric Pressure, Magnetic Field, etc.) are neglected (i.e., T_o = fr):

(A) A 10 MHz Rb Oscillator:

$$TBC_{Rb} = \frac{f_T - f_o}{Df_r} = \frac{1\ Hz}{(1E\text{-}11/month^*)\ (900E+6)}$$

$$TBC_{Rb} = 111\ months$$

(B) A 10 MHz Precision Crystal Oscillator:

$$TBC_{xtal} = \frac{1\ Hz}{(5E\text{-}10/day^*)\ (900E+6)}$$

$$TBC_{xtal} = 2.2\ days$$

(*Convert to seconds)

ERROR BUDGET NOTES

ENVIRONMENTAL CHANGES vs. PERFORMANCE CHARACTERISTICS OF A Rb OSCILLATOR

Ball Efratom Division

	SHORT-TERM STABILITY	PHASE NOISE	LONG-TERM STABILITY	AGING	TIME KEEPING ABILITY	POWER CONSUMPTION	WARM-UP TIME	REMARKS
TEMPERATURE			X		X	X	X	MAJOR CONTRIBUTOR
MAGNETIC (AC) FIELD (DC)	X	X	X X		X X		X	MINOR CONTRIBUTOR
ALTITUDE (PRESSURE)			X		X			MINOR CONTRIBUTOR
SUPPLY VOLTAGE TO OSCILLATOR			X		X	X	X	MINOR CONTRIBUTOR
NUCLEAR (DOSE RATE) RADIATION (TOTAL DOSE)	X	X	X		X X			MINOR CONTRIBUTOR
LINEAR ACCELERATION			X		X			NEGLIGIBLE
VIBRATION	X	X	X		X		X	WORST ENEMY OF PRECISION OSCILLATORS

TIME ERROR CALCULATION NOTES

Ball Efratom Division

OCSCILLATOR FREQUENCY OFFSET CAUSED BY:	TIME ERROR AFFECTED: -LINEARILY -QUADRADICALLY	FREQ. OFFSET HAS A POSITIVE OR NEGATIVE COEFFICIENT OR IS INDEPENDENT OF DIRECTION OF CHANGE[(1)]	TIME ERROR IS CALCULATED BY:
TEMPERATURE CHANGES	LINEAR	INDEPENDENT	$t_{(error)} = \Delta f/f \times t$(time in sec.)
MAGNETIC FIELD CHANGES	LINEAR	POSITIVE	same
ALTITUDE CHANGES	LINEAR	NEGATIVE	same
SUPPLY VOLTAGE CHANGES	LINEAR	POSITIVE	same
ACCELERATION CHANGES	LINEAR	INDEPENDENT	same
VIBRATION	LINEAR	INDEPENDENT	same
NUCLEAR RADIATION	LINEAR	INDEPENDENT	same
OSCILLATOR AGING (a)	QUADRATIC	N/A	$t_{(error)} = 1/2\ at^2$
TOTAL		NOTE:[(1)] NEGATIVE COEFFICIENTS APPLY TO EFRATOM Rb OSCILLATORS	AN ACCEPTABLE REPRESENTATION OF TOTAL TIME ERROR IS "RSS" OF ALL THE FREQ OFFSETS

TIME ERROR DUE TO "AGING" OF ATOMIC OSCILLATORS

$$\Delta t = \underbrace{.025 \times D \times t^2}_{\Delta t_D} + \underbrace{.36 \times \sigma_{FF} \times t}_{\Delta t_S}$$

Δt_D (deterministic)

Δt_S (stochastic)

where

Δt	=	time error in nsec at time t
t	=	elapsed time in hours
D	=	aging rate in units of parts in 10^{11} per month.
σ_{FF}	=	Allan deviation (root Allan variance) at flicker floor in units of parts in 10^{13}
t_{FF}	=	Averaging time at which Allan variance reaches flicker floor (not part of above formula)

The above formula does not include the contribution to the time error from frequency error that exists at t = 0. (Oscillator Frequency Offset)

The above formula is valid for $t \geq t_{FF}$. For $t < t_{FF}$ it underestimates the time error.

Example: FRK-H spec

aging rate = 1E-11/month $\therefore$ D = 1

flicker floor = 3E-13 @ ~1000 sec

$\therefore \sigma_{FF} = 3$ and $t_{FF} = 0.3$ h

$$\Delta t = \overbrace{.025t^2}^{\Delta t_D} + \overbrace{1.08t}^{\Delta t_S}$$

From this formula, it follows that:

t (h)	TOTAL	DETERMINISTIC	STOCHASTIC
	Δt (nsec)	Δt_D (nsec)	Δt_S (nsec)
.3	.33	.0023	.324
1.0	1.105	.025	1.08
10	13.3	2.5	10.8
24	40.3	14.4	26.0

OPERATIONAL CONSIDERATIONS

Any precision device operating in a stability range of 0.000 000 000 000 15 per day will be greatly influenced by external environments. For example, a rubidium oscillator used as a timing device in a laboratory may accumulate an error of 2 to 5 nano sec in a four hour period. Placing the same oscillator in a hostile environment such as a fighter aircraft on a 4 hour tactical mission, the error in time may be a microsecond. Although various environments play a part, vibration is the biggest contributor. The oscillator performance graphs shown in Sections 3.0, 4.0, and 5.0 are portrayed as separate and distinct factors affecting performance. To demonstrate performance in a tactical environment, these influences and resultant performance characteristics are now applied simultaneously.

Rb OSCILLATOR EXAMPLE ERROR BUDGET ANALYSIS

A very hostile tactical environment is generated by a fighter aircraft. As a result, performance characteristics of the oscillator can generally be considered as worst case. The following is an example of such a tactical fighter environment using the Efratom M3000 Rb oscillator as our model from which this error budget analysis is derived.

QUARTZ OSCILLATOR EXAMPLE ERROR BUDGET ANALYSIS

The Rubidium M3000 example is followed by the Efratom Quartz Crystal Oscillator, Model EMXO applied to the exact same mission, for comparision.

FIGHTER AIRCRAFT 4-HOUR MISSION PROFILE

TIME ERROR ANALYSIS M3000 RUBIDIUM OSCILLATOR

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
M3000 RUBIDIUM OSC.

PART-1-

12-8-91,HUGO
M3000FTR.WK1

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	MISSION ACTIONS	LINEAR ACCEL. in G's	ACCEL TIME (SEC)	ACCUMUL TIME ERROR (SEC)
	PARAMETER					ACCEL.
	EXPECTED FREQ OFFSET OF OSC					4.00E-12 per G
	MODEL M3000					
	TIME/FREQ HANDBOOK					SECTION 4
	NOTES:					NOTE-1-
1	0-1,800	1800	GROUND	0	0	0.00E+00
2	1,800-1,830	30	CLIMB	1.5	30	1.80E-10
3	1,830-2,010	180	CLIMB	1.5	30	3.60E-10
4	2,010-4,860	2850	WUTx6	2	180	1.80E-09
5	4,860-5,040	180	CLIMB	1.5	30	1.98E-09
6	5,040-6,700	1660	WUTx1	2.5	45	2.43E-09
7	6,700-6,730	30	DECEL	-1.5	30	2.25E-09
8	6,730-6,760	30	DECEL	-1.5	30	2.07E-09
9	6,760-6,790	30	DECEL	-1	30	1.95E-09
10	6,790-6,850	60	DECEL	-1	60	1.71E-09
11	6,850-7,090	240	LEVEL	0	0	1.71E-09
12	7,090-7,120	30	DECEL	-1.5	30	1.53E-09
13	7,120-8,520	1400	LEVEL	0	0	1.53E-09
14	8,520-8,700	180	DECEL	-1.5	30	1.35E-09
15	8,700-9,120	420	LEVEL	0	0	1.35E-09
16	9,120-9,480	360	DECEL	-1.5	30	1.17E-09
17	9,480-11,520	2040	LEVEL	0	0	1.17E-09
18	11,520-11,530	10	CLIMB	5.6	10	1.39E-09
19	11,530-11,770	240	LEVEL	0	0	1.39E-09
20	11,770-11,950	180	CLIMB	1.5	30	1.57E-09
21	11,950-13,400	1450	LEVEL	0	0	1.57E-09
22	13,400-14,400	1000	DECEL	-1.5	180	4.94E-10

TOTAL ACCUMULATED TIME ERROR
PER PARAMETER AT LANDING 4.94E-10

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
M3000 RUBIDIUM OSC.

PART-2-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	ALTITUDE in FT.	ACCUMUL TIME ERROR (SEC)	TEMP in DEG.C	DELTA TEMP DEG.C	ACCUMUL TIME ERROR (SEC)
	PARAMETER			PRESSURE			TEMP
	EXPECTED FREQ			-1.00E-15			2.22E-12
	OFFSET OF OSC			per FT.			per DEG.C
				-4.00E-11			3.00E-10
	MODEL M3000			40K ft			-55 to 80C
	TIME/FREQ HANDBOOK			SECTION 3			SECTION 3
	NOTES:			NOTE-2-			NOTE-3-
1	0-1,800	1800	0	0.00E+00	50		0.00E+00
2	1,800-1,830	30	4000	-1.20E-10	79	29	1.93E-09
3	1,830-2,010	180	25000	-4.62E-09	52	2	2.73E-09
4	2,010-4,860	2850	25000	-7.59E-08	52	2	1.54E-08
5	4,860-5,040	180	40000	-8.31E-08	41	-9	1.18E-08
6	5,040-6,700	1660	40000	-1.49E-07	41	-9	-2.14E-08
7	6,700-6,730	30	33000	-1.50E-07	49	-1	-2.15E-08
8	6,730-6,760	30	25000	-1.51E-07	52	2	-2.13E-08
9	6,760-6,790	30	28000	-1.52E-07	50	0	-2.13E-08
10	6,790-6,850	60	25000	-1.54E-07	52	2	-2.11E-08
11	6,850-7,090	240	25000	-1.60E-07	62	12	-1.47E-08
12	7,090-7,120	30	20000	-1.60E-07	65	15	-1.37E-08
13	7,120-8,520	1400	20000	-1.88E-07	65	15	3.30E-08
14	8,520-8,700	180	5000	-1.89E-07	76	26	4.34E-08
15	8,700-9,120	420	5000	-1.91E-07	76	26	6.77E-08
16	9,120-9,480	360	500	-1.91E-07	84	34	9.49E-08
17	9,480-11,520	2040	500	-1.92E-07	84	34	2.49E-07
18	11,520-11,530	10	5000	-1.92E-07	76	26	2.50E-07
19	11,530-11,770	240	5000	-1.94E-07	76	26	2.63E-07
20	11,770-11,950	180	25000	-1.98E-07	52	2	2.64E-07
21	11,950-13,400	1450	25000	-2.34E-07	52	2	2.71E-07
22	13,400-14,400	1000	0	-2.34E-07	50	0	2.71E-07
	TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING			-2.34E-07			2.71E-07

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
M3000 RUBIDIUM OSC.

PART-3-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	POWER SUPPLY BUS VOLTS	DELTA VOLTS VDC	ACCUMUL TIME ERROR (SEC)	EARTH'S MAG. FIELD DELTA	ACCUMUL TIME ERROR (SEC)
	PARAMETER				P.S.VOLTS		MAG.FIELD
	EXPECTED FREQ OFFSET OF OSC MODEL M3000				4.00E-12 per VOLT 4.00E-11 10vdc RISE		2.40E-11 per GAUSS
	TIME/FREQ HANDBOOK				SECTION 3		SECTION 3
	NOTES:				NOTE-4-		NOTE-5-
1	0-1,800	1800	26		0.00E+00	0	0.00E+00
2	1,800-1,830	30	30	4	4.80E-10	0.132	9.50E-11
3	1,830-2,010	180	29	3	2.64E-09	0.132	6.65E-10
4	2,010-4,860	2850	26	0	2.64E-09	0.132	9.69E-09
5	4,860-5,040	180	30	4	5.52E-09	0.132	1.03E-08
6	5,040-6,700	1660	26	0	5.52E-09	0.132	1.55E-08
7	6,700-6,730	30	26	0	5.52E-09	0.132	1.56E-08
8	6,730-6,760	30	26	0	5.52E-09	0.132	1.57E-08
9	6,760-6,790	30	26	0	5.52E-09	0.132	1.58E-08
10	6,790-6,850	60	26	0	5.52E-09	0.132	1.60E-08
11	6,850-7,090	240	26	0	5.52E-09	0.132	1.68E-08
12	7,090-7,120	30	26	0	5.52E-09	0.132	1.69E-08
13	7,120-8,520	1400	26	0	5.52E-09	0.132	2.13E-08
14	8,520-8,700	180	24	-2	4.08E-09	0.132	2.19E-08
15	8,700-9,120	420	26	0	4.08E-09	0.132	2.32E-08
16	9,120-9,480	360	24	-2	1.20E-09	0.132	2.43E-08
17	9,480-11,520	2040	26	0	1.20E-09	0.132	3.08E-08
18	11,520-11,530	10	29	3	1.32E-09	0.132	3.08E-08
19	11,530-11,770	240	26	0	1.32E-09	0.132	3.16E-08
20	11,770-11,950	180	30	4	4.20E-09	0.132	3.22E-08
21	11,950-13,400	1450	26	0	4.20E-09	0.132	3.67E-08
22	13,400-14,400	1000	26	0	4.20E-09	0.132	3.99E-08
TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING					4.20E-09		3.99E-08

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
M3000 RUBIDIUM OSC.

PART-4-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	VIBRATION SPECTRAL DENSITY G-VERT. G SQ/Hz	G-LAT. G SQ/Hz	G-LONG. G SQ/Hz	TOTAL G-rms	ACCUMUL TIME ERROR (SEC)
	PARAMETER						VIBRAT'N
	EXPECTED FREQ OFFSET OF OSC MODEL M3000					5.5 G-rms	1.9E-11 per SEC. 70 nsec/HR
	TIME/FREQ HANDBOOK						SECTION 4
	NOTES:						NOTE-6-
1	0-1,800	1800	0.0	0.0	0.0	0.0	0.00E+00
2	1,800-1,830	30	1.6	1.7	2.2	5.5	5.83E-10
3	1,830-2,010	180	0.9	0.5	1.5	2.9	2.43E-09
4	2,010-4,860	2850	0.7	0.7	1.3	2.7	2.96E-08
5	4,860-5,040	180	0.9	0.5	1.5	2.9	3.15E-08
6	5,040-6,700	1660	0.7	0.7	1.3	2.7	4.73E-08
7	6,700-6,730	30	0.9	0.3	1.5	2.7	4.76E-08
8	6,730-6,760	30	0.9	0.3	1.5	2.7	4.79E-08
9	6,760-6,790	30	0.7	0.7	1.3	2.7	4.82E-08
10	6,790-6,850	60	0.9	0.3	1.5	2.7	4.88E-08
11	6,850-7,090	240	0.0	0.0	0.0	0.0	4.88E-08
12	7,090-7,120	30	0.9	0.3	1.5	2.7	4.90E-08
13	7,120-8,520	1400	0.0	0.0	0.0	0.0	4.90E-08
14	8,520-8,700	180	1.5	1.6	2.1	5.2	5.24E-08
15	8,700-9,120	420	0.0	0.0	0.0	0.0	5.24E-08
16	9,120-9,480	360	1.5	1.6	2.1	5.2	5.90E-08
17	9,480-11,520	2040	0.0	0.0	0.0	0.0	5.90E-08
18	11,520-11,530	10	1.9	2.1	2.4	6.4	5.92E-08
19	11,530-11,770	240	0.0	0.0	0.0	0.0	5.92E-08
20	11,770-11,950	180	0.7	0.7	1.3	2.7	6.09E-08
21	11,950-13,400	1450	0.0	0.0	0.0	0.0	6.09E-08
22	13,400-14,400	1000	1.5	1.6	2.1	5.2	7.93E-08

TOTAL ACCUMULATED TIME ERROR
PER PARAMETER AT LANDING 7.93E-08

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
M3000 RUBIDIUM OSC.

PART-5-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	ACCUMUL TIME ERROR (SEC)	ACCUMUL TIME ERROR (SEC)	ACCUMUL TIME ERROR (SEC)
	PARAMETER		RETRACE	WARMUP	AGING
	EXPECTED FREQ		1.00E-11	1.00E-09	1.14E-17
	OFFSET OF OSC			2.00E-10	per SEC.
				3.00E-11	3.60E-10
	MODEL M3000			5.00E-12	1st YEAR
	TIME/FREQ HANDBOOK		SECTION 3	SECTION 3	SECTION 3
	NOTES:		NOTE-7-	NOTE-8-	NOTE-9-
1	0-1,800	1800	1.80E-08	6.00E-07	1.85E-11
2	1,800-1,830	30	1.83E-08	6.01E-07	1.85E-11
3	1,830-2,010	180	2.01E-08	6.06E-07	1.87E-11
4	2,010-4,860	2850	4.86E-08	6.92E-07	6.50E-11
5	4,860-5,040	180	5.04E-08	6.93E-07	6.52E-11
6	5,040-6,700	1660	6.70E-08	7.01E-07	8.10E-11
7	6,700-6,730	30	6.73E-08	7.01E-07	8.10E-11
8	6,730-6,760	30	6.76E-08	7.01E-07	8.10E-11
9	6,760-6,790	30	6.79E-08	7.01E-07	8.10E-11
10	6,790-6,850	60	6.85E-08	7.02E-07	8.10E-11
11	6,850-7,090	240	7.09E-08	7.03E-07	8.13E-11
12	7,090-7,120	30	7.12E-08	7.03E-07	8.13E-11
13	7,120-8,520	1400	8.52E-08	7.10E-07	9.25E-11
14	8,520-8,700	180	8.70E-08	7.11E-07	9.27E-11
15	8,700-9,120	420	9.12E-08	7.13E-07	9.37E-11
16	9,120-9,480	360	9.48E-08	7.15E-07	9.44E-11
17	9,480-11,520	2040	1.15E-07	7.25E-07	1.18E-10
18	11,520-11,530	10	1.15E-07	7.25E-07	1.18E-10
19	11,530-11,770	240	1.18E-07	7.26E-07	1.19E-10
20	11,770-11,950	180	1.19E-07	7.27E-07	1.19E-10
21	11,950-13,400	1450	1.34E-07	7.35E-07	1.31E-10
22	13,400-14,400	1000	1.44E-07	7.40E-07	1.36E-10
TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING			1.44E-07	7.40E-07	1.36E-10

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
M3000 RUBIDIUM OSC.

PART-6-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	ACCUMUL TIME ERROR (SEC)	COMBINED ENVIRONMT TIME ERROR	COMBINED ENVIRONMT TIME ERROR
	PARAMETER		LAST CAL	WORST	RSS
	EXPECTED FREQ OFFSET OF OSC MODEL M3000		3.00E-11 per MO. (no cal for 1 MO)	CASE SCENARIO	(ROOT SUM SQUARED) -TYPICAL-
	TIME/FREQ HANDBOOK		DATA SHEETS		
	NOTES:		NOTE-10-	NOTE-11-	NOTE-12-
1	0-1,800	1800	5.40E-08	6.72E-07	6.03E-07
2	1,800-1,830	30	5.49E-08	6.77E-07	6.04E-07
3	1,830-2,010	180	6.03E-08	6.91E-07	6.10E-07
4	2,010-4,860	2850	1.46E-07	8.70E-07	7.14E-07
5	4,860-5,040	180	1.51E-07	8.72E-07	7.17E-07
6	5,040-6,700	1660	2.01E-07	8.69E-07	7.49E-07
7	6,700-6,730	30	2.02E-07	8.70E-07	7.50E-07
8	6,730-6,760	30	2.03E-07	8.70E-07	7.51E-07
9	6,760-6,790	30	2.04E-07	8.71E-07	7.51E-07
10	6,790-6,850	60	2.06E-07	8.73E-07	7.52E-07
11	6,850-7,090	240	2.13E-07	8.85E-07	7.57E-07
12	7,090-7,120	30	2.14E-07	8.87E-07	7.57E-07
13	7,120-8,520	1400	2.56E-07	9.73E-07	7.85E-07
14	8,520-8,700	180	2.61E-07	9.93E-07	7.89E-07
15	8,700-9,120	420	2.74E-07	1.04E-06	7.98E-07
16	9,120-9,480	360	2.84E-07	1.08E-06	8.07E-07
17	9,480-11,520	2040	3.46E-07	1.33E-06	8.73E-07
18	11,520-11,530	10	3.46E-07	1.34E-06	8.73E-07
19	11,530-11,770	240	3.53E-07	1.36E-06	8.82E-07
20	11,770-11,950	180	3.59E-07	1.37E-06	8.86E-07
21	11,950-13,400	1450	4.02E-07	1.41E-06	9.23E-07
22	13,400-14,400	1000	4.32E-07	1.48E-06	9.44E-07
TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING			4.32E-07	1.48E-06	9.44E-07

M3000 NOTES

1. The acceleration sensitivity is: (4E-12) (±G's) (Event Time) +Prev. Accum. Time.

2. Altitude sensitivity is -4E-11 at 40,000 ft. For simplicity, use a linear fit, -4E-11/40,000 ft. = (-)1E-15/ft.

3. Temp coefficient is (3E-10/135)(temp delta from 50C)
   The temperature is not a linear function over this range. But due to the small range of this analysis, consider it linear.

****DEPOT CALIBRATE UNIT AT 50°C BASEPLATE TEMP.****

4. Supply voltage change sensitivity is 1E-11 for a +10% change over the OPS range of 22 to 32 Vdc. To make it simple this is about 4E-11 over the range, so 4E-11/10(delta volts)(event time).

****DEPOT CALIBRATE UNIT AT 26Vdc SUPPLY VOLTAGE.****

5. Magnetic field sensitivity is mainly from the earth's field. Use 33% of earth's mag. field (~0.4 gauss) as a constant offset, so 2.4E-11 (33% of 0.4 gauss)(event time).

6. Vibration sensitivity is from 3 spectral densities added together. Also, 70 nanoSEC/HR has been measured for environments such as this. The unit with which this measurement was made had a 2E-9/G class crystal. A ~5E-10/G class crystal in the M3000 will improve the performance. The formula used is: (70E-9/3600)(G-rms/5.5)(event time).

****PERFORMANCE DEPENDS HEAVILY ON THE FREQ. SPECTRUM.****

7. Retrace: since the Rb freq. offset will not return to the original freq. to better than 1E-11, a permanent offset of 1E-11 was used, so 1E-11 (event time).

8. Assume unit turn-on at start of 30 min. GRD. time, therefore:

0 to 5 min.,	ave. offset of 1E-9
5 to 30 min.,	ave. offset of 2E-10
30 to 51 min.,	ave. offset of 3E-11
51 to END	ave. offset of 5E-12

9. A 1-year old unit will have a drift of ~3.6E-10 for the first year. The formula for drift is: Time Error = 1/2(drift)(time squared). If the event time is in seconds, convert everything to seconds. So: 1/2(3.6E-10/one year's worth of seconds)(event time in sec squared).

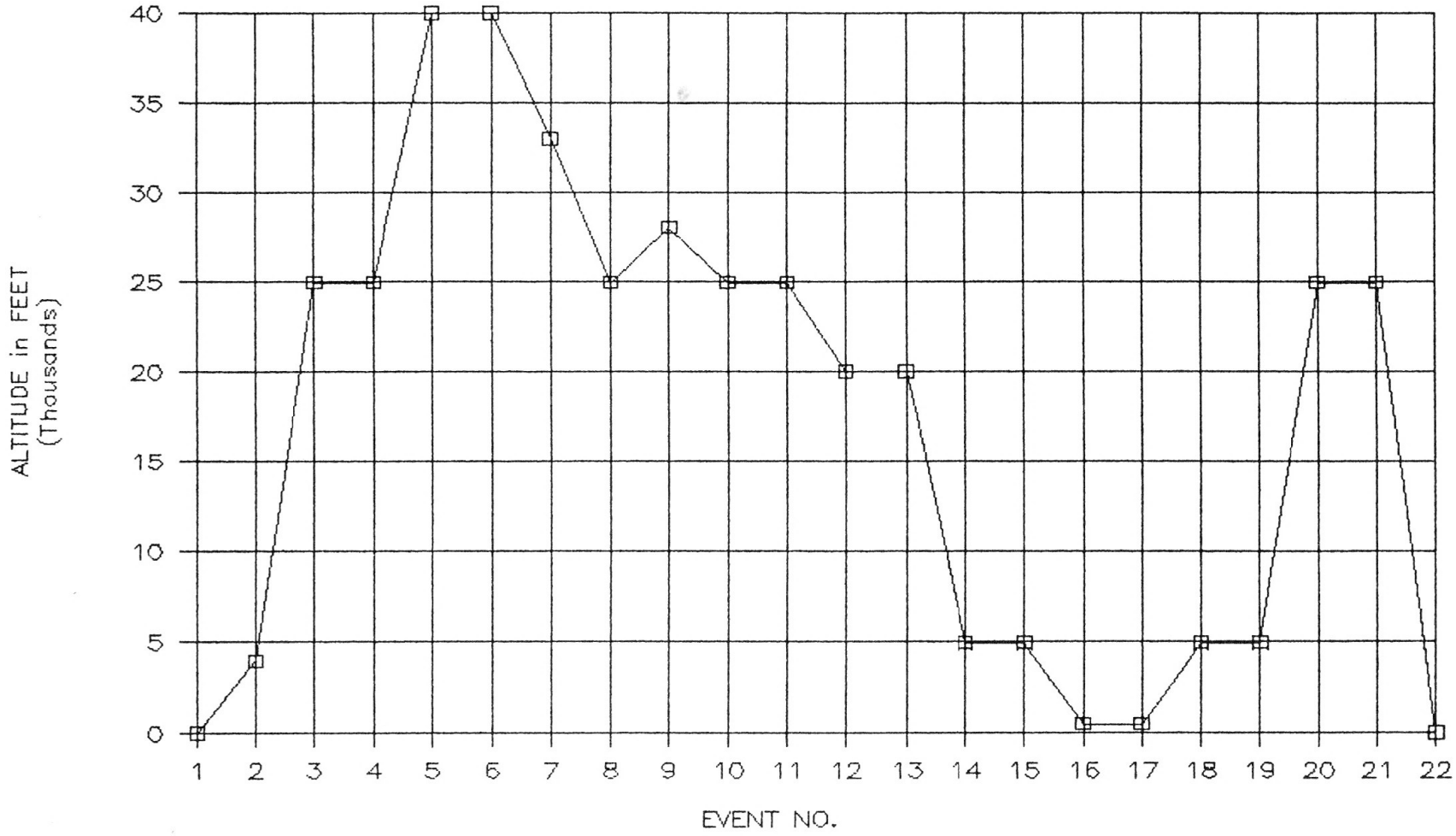
10. A unit 1-year old not calibrated for one month, will have drifted about 3E-11. Use as a constant offset for the length of mission.

11. This column represents a worst case total with all errors added in an algebraic manner.

12. This represents the most likely error which from experience comes closer to that of the Root Sum Square (RSS) in actual operations. Use this as the typical expected result.

TYPICAL MISSION PROFILE
FIGHTER AIRCRAFT

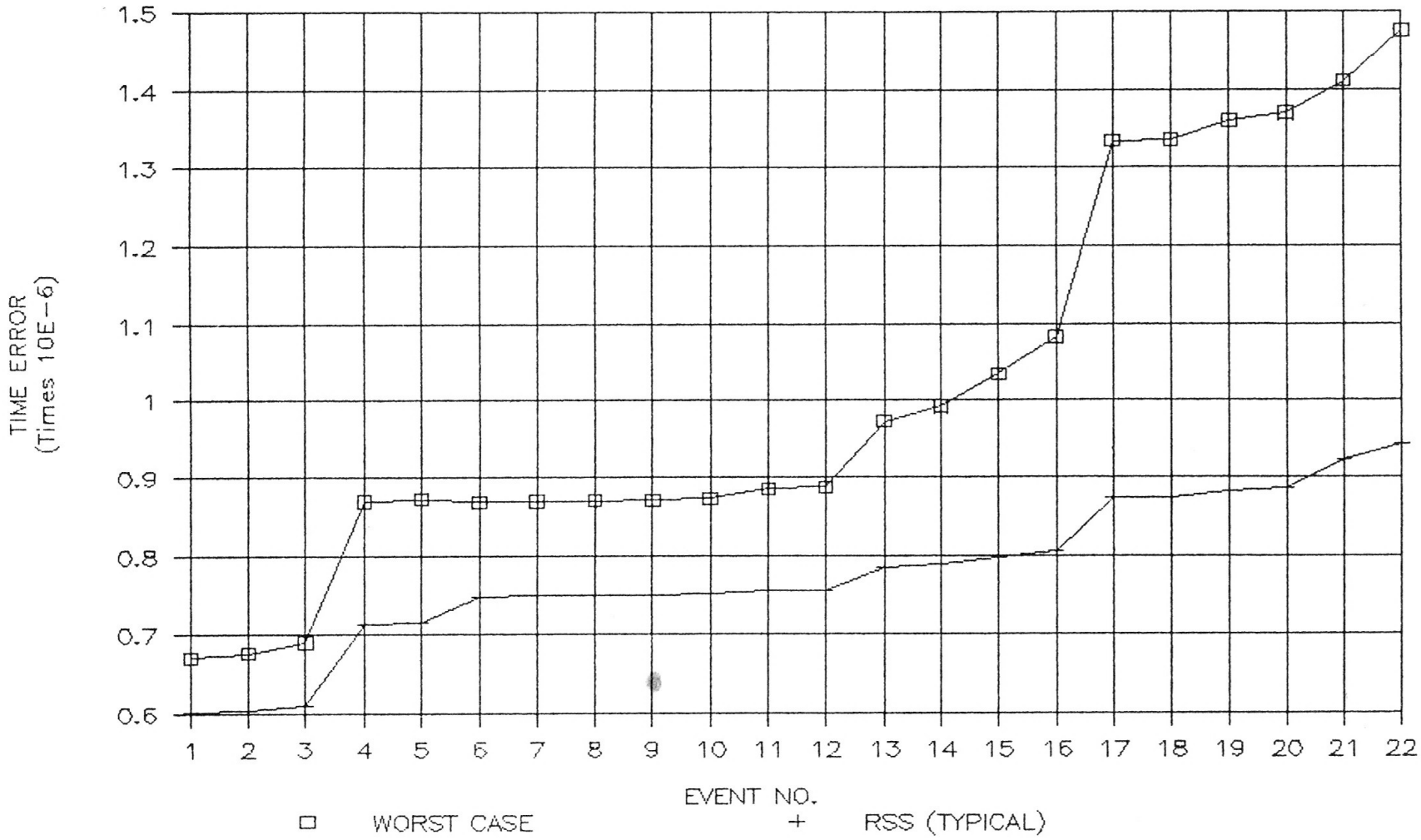
Ball Efratom Division



9.17

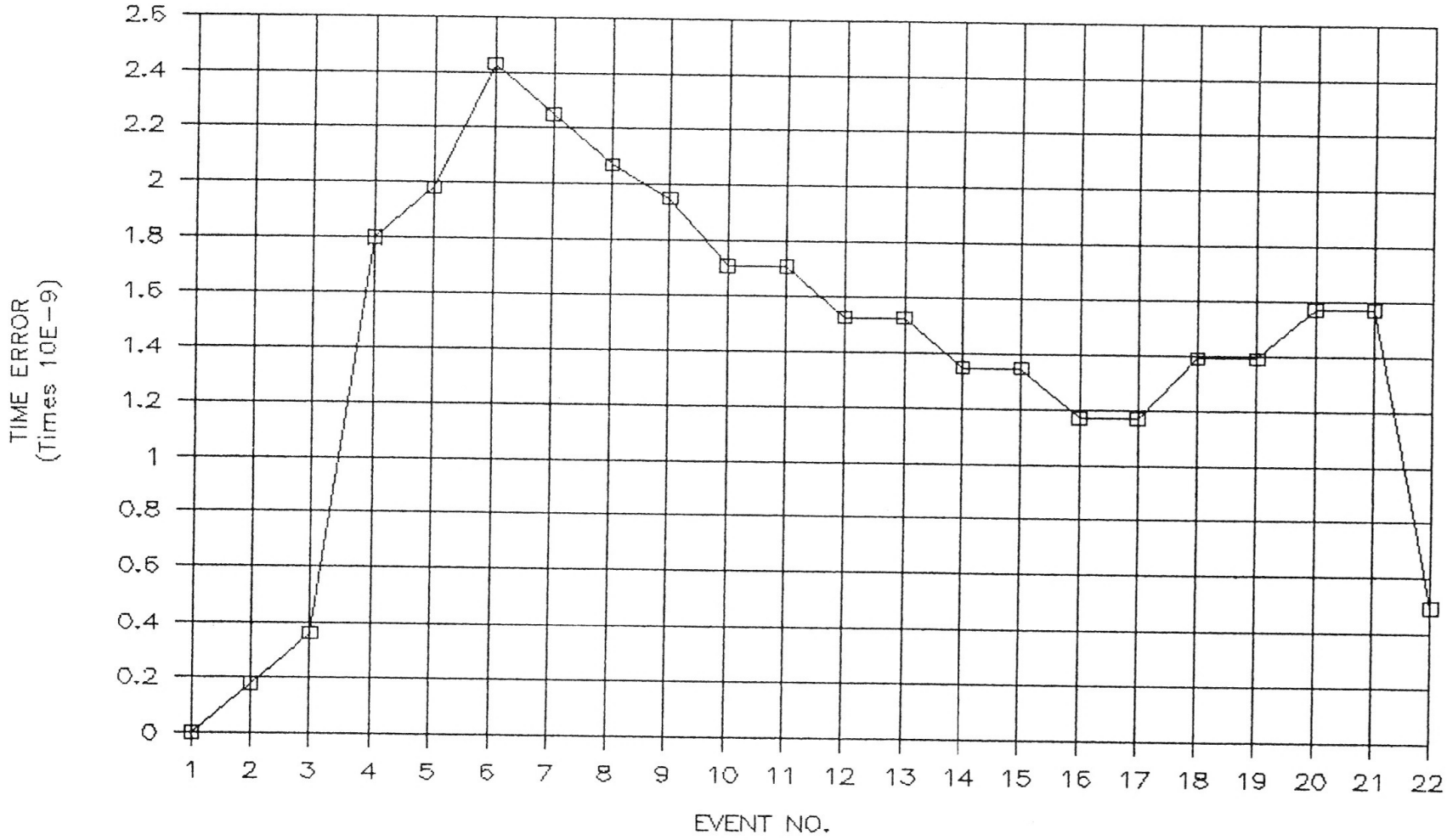
TOTAL ACCUM. TIME ERROR, COMBINED ENVIRONMENTS

Ball Efratom Division



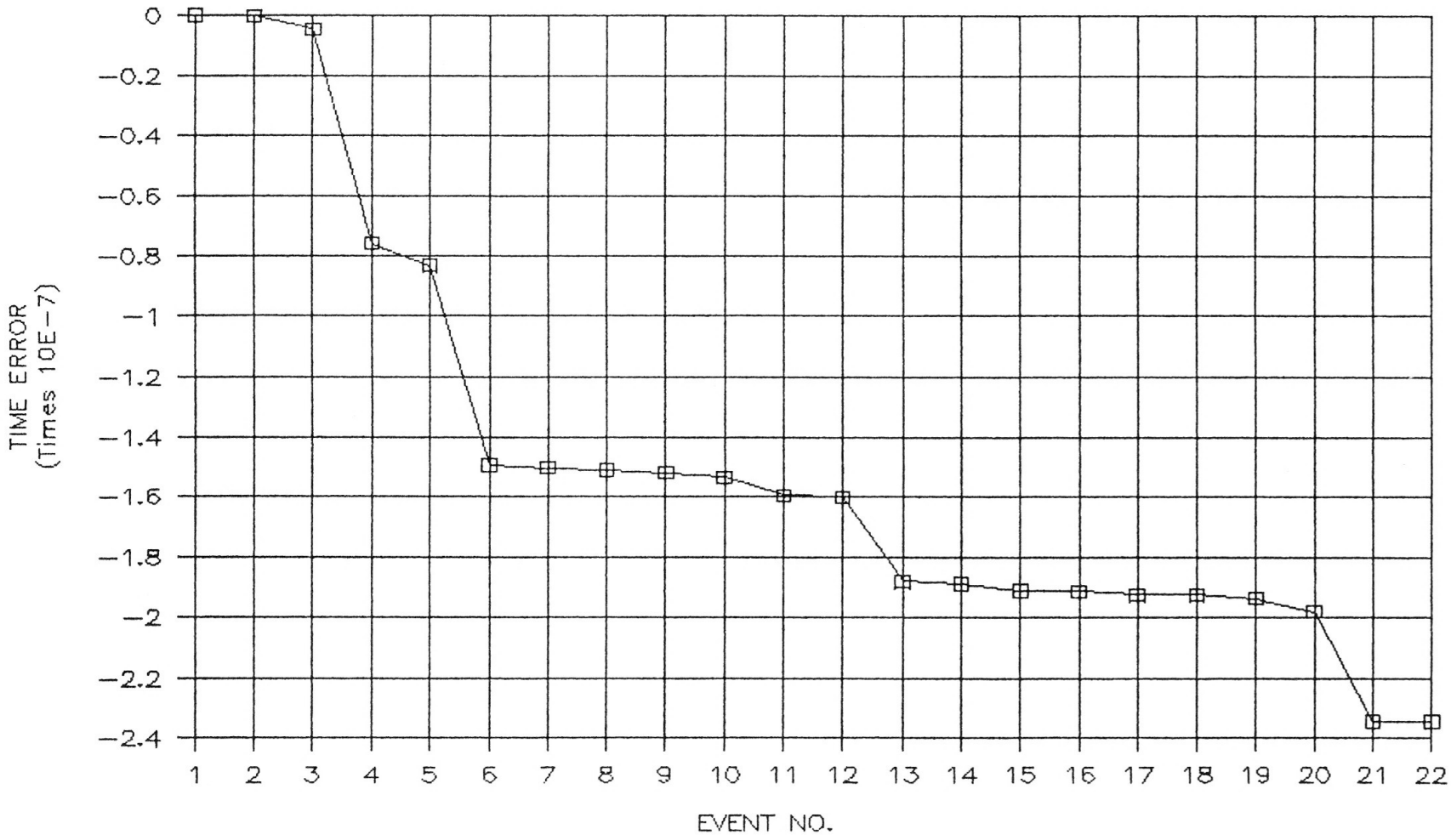
ACCUM. TIME ERROR, ACCELERATION

Ball Efratom Division



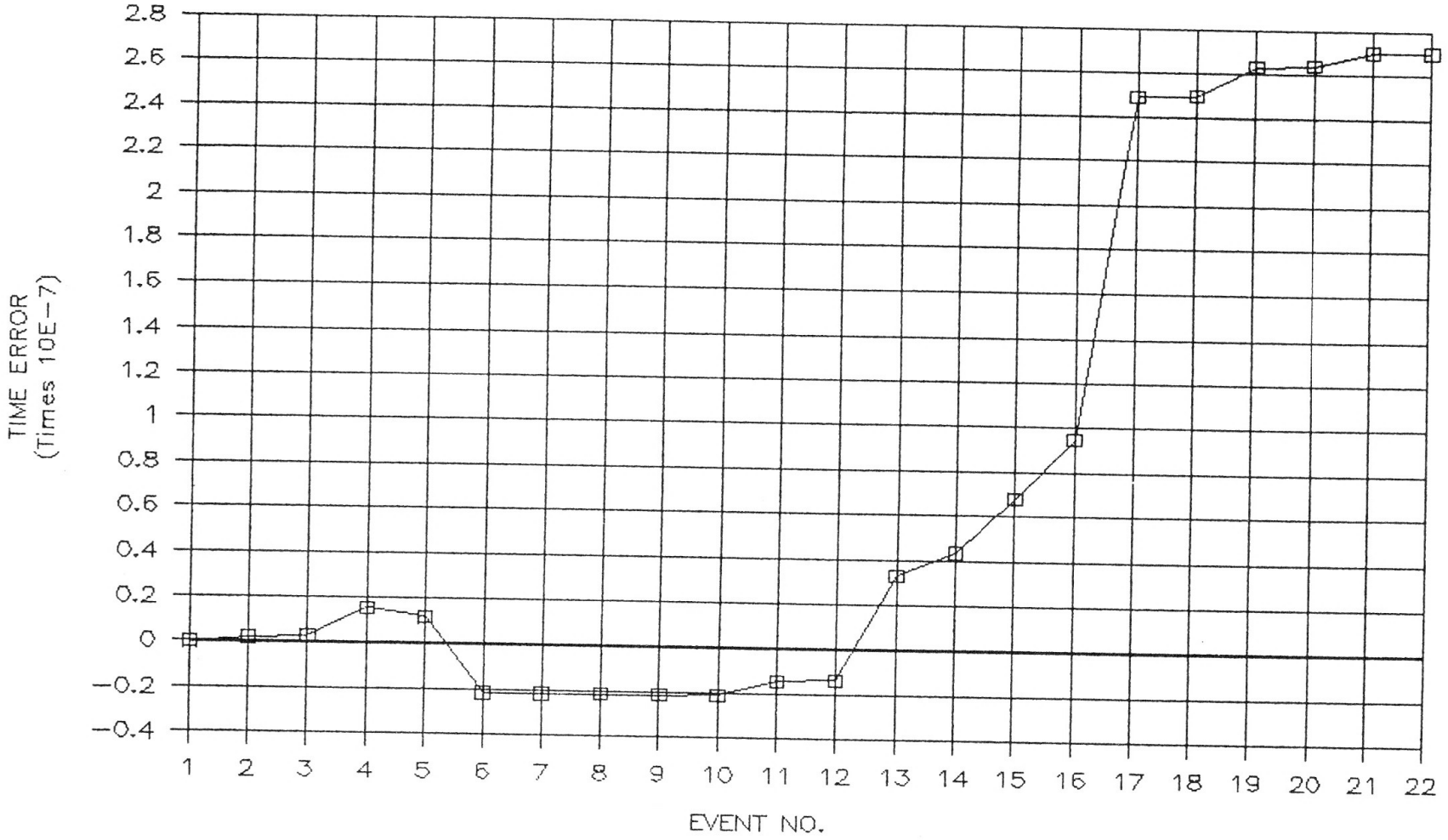
ACCUM. TIME ERROR, PRESSURE

Ball Efratom Division



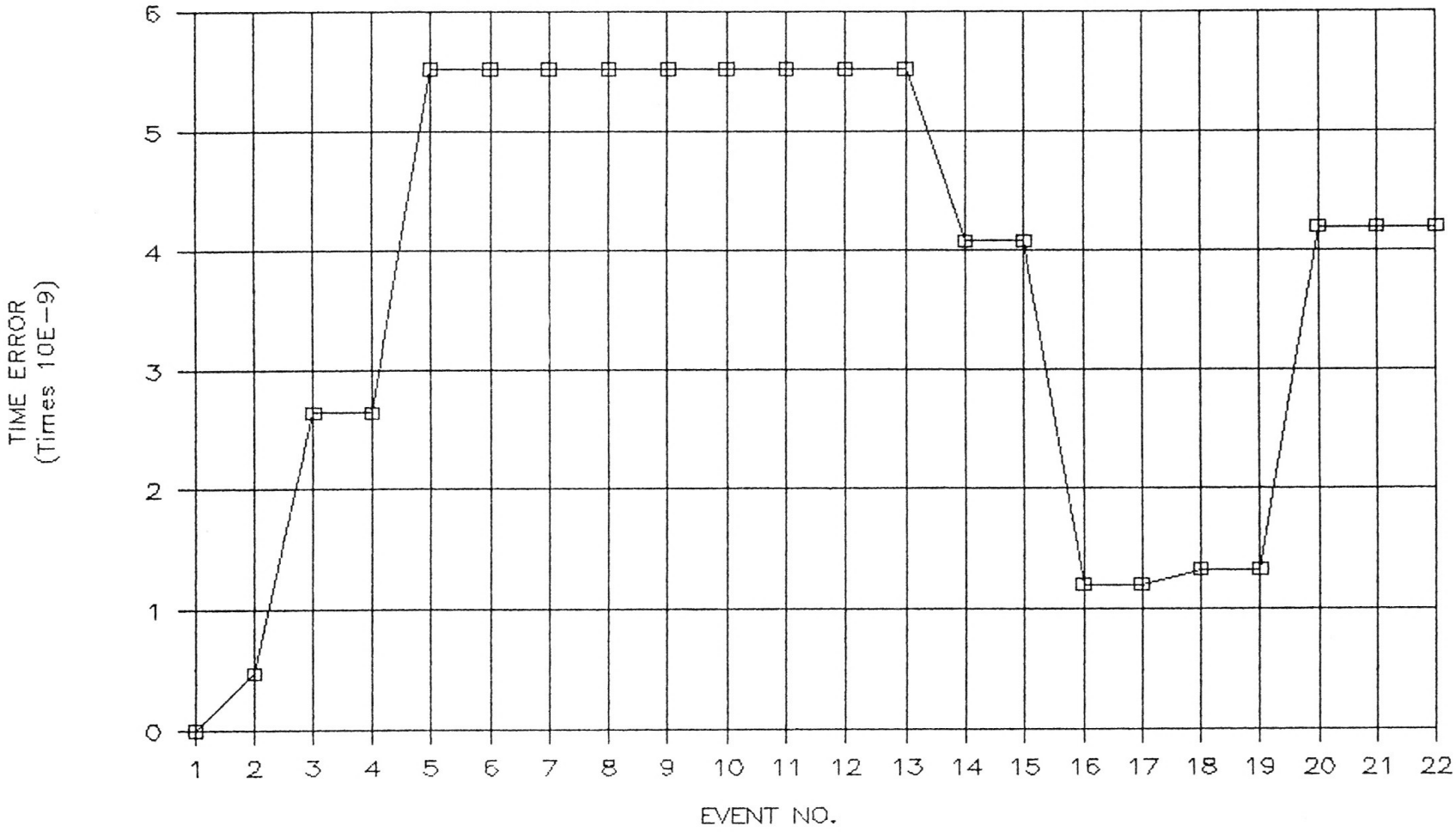
ACCUM. TIME ERROR, TEMPERATURE

Ball Efratom Division



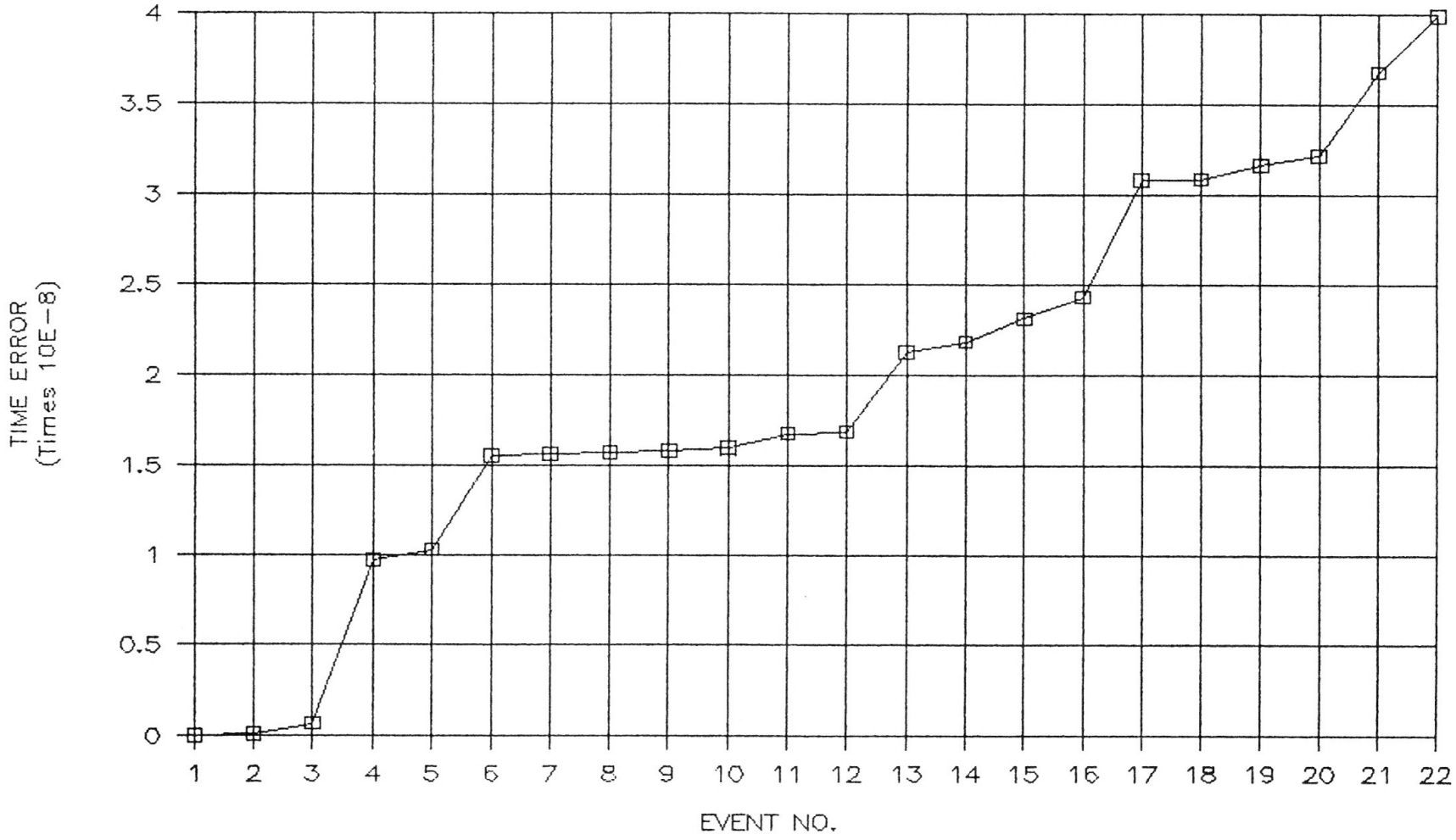
ACCUM. TIME ERROR, VOLTS

Ball Efratom Division



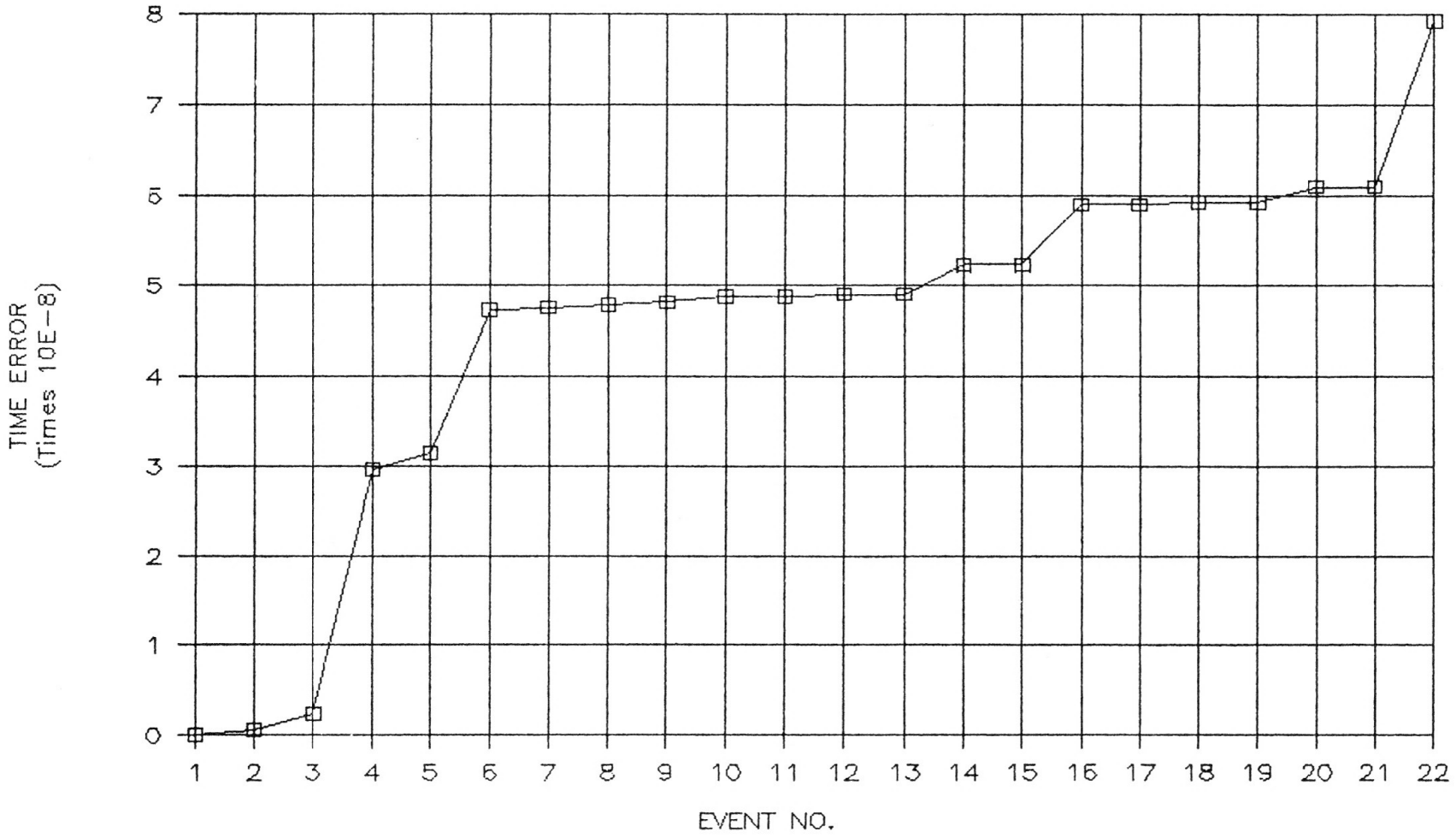
ACCUM. TIME ERROR, MAGNETICS

Ball Efratom Division



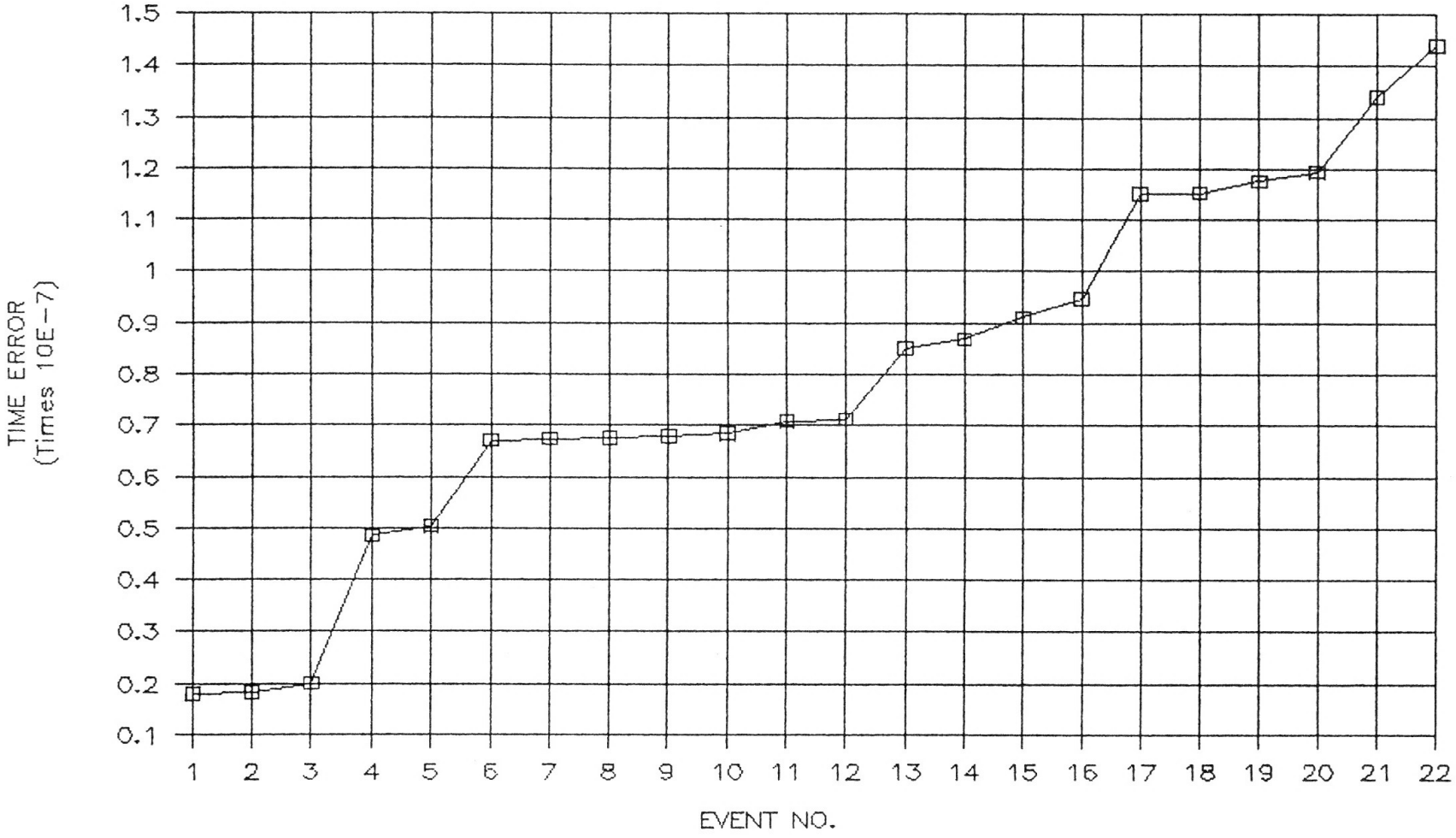
ACCUM. TIME ERROR, VIBRATION

Ball Efratom Division



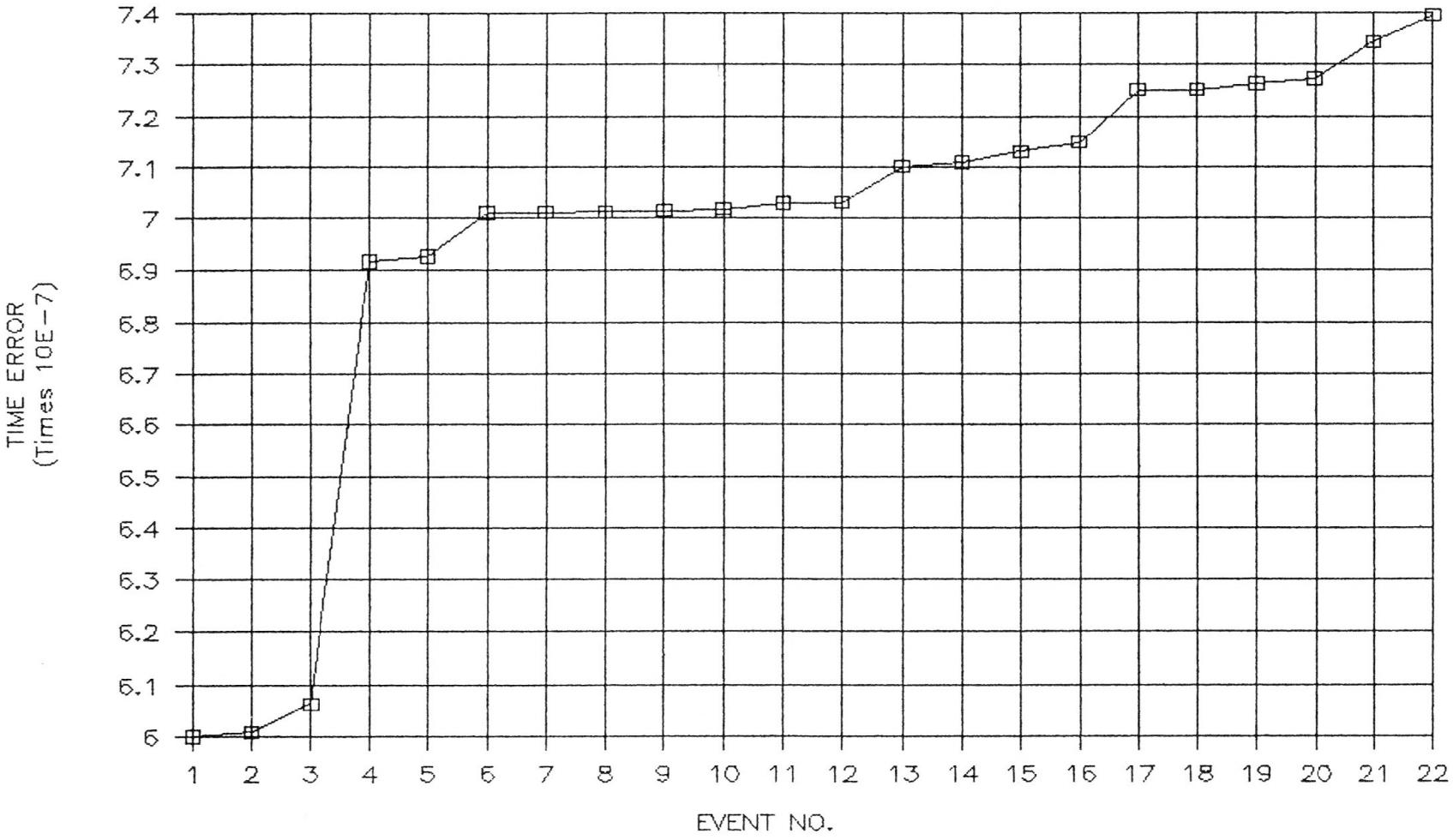
ACCUM. TIME ERROR, RETRACE

Ball Efratom Division



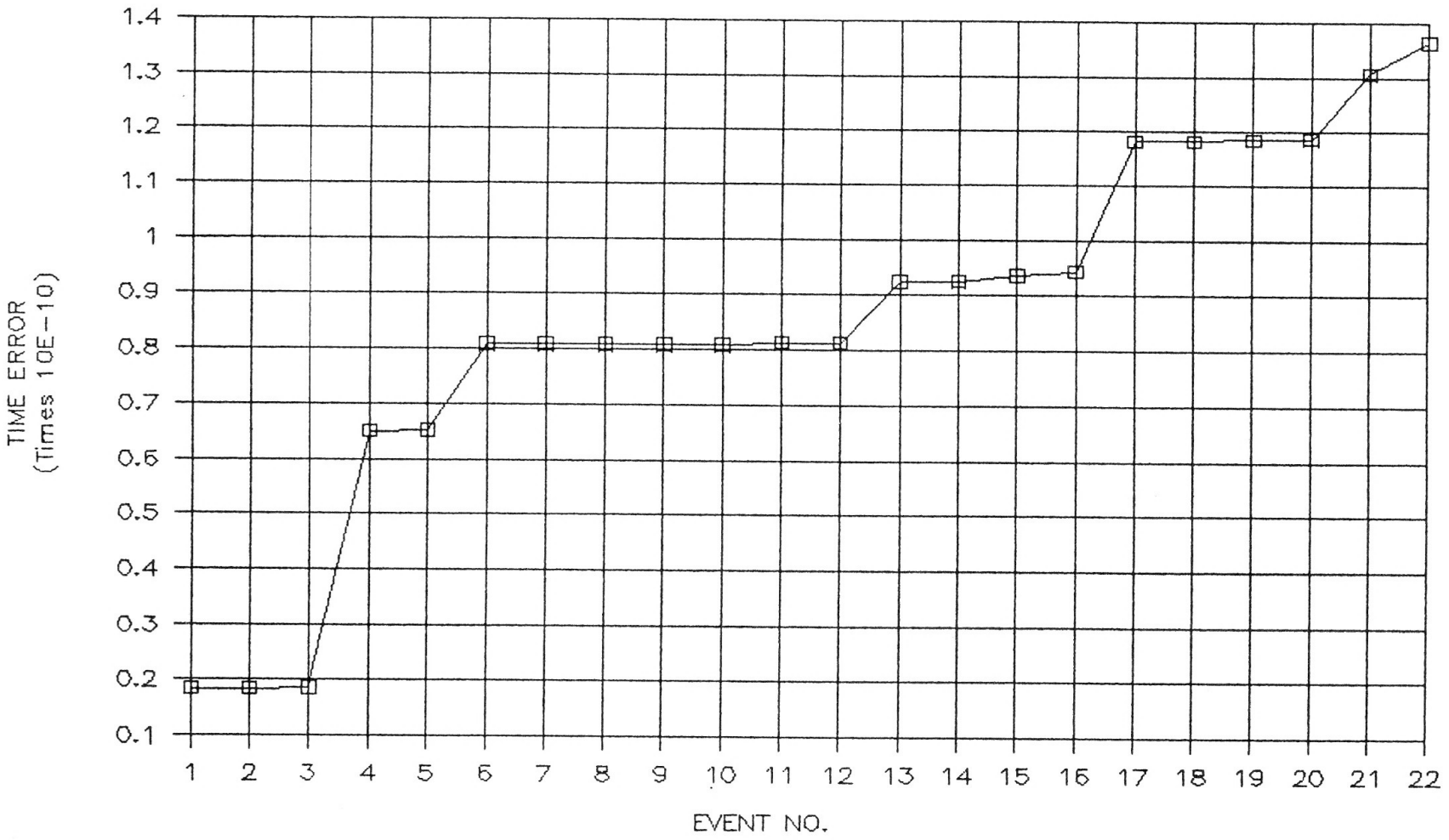
ACCUM. TIME ERROR, WARM-UP

Ball Efratom Division



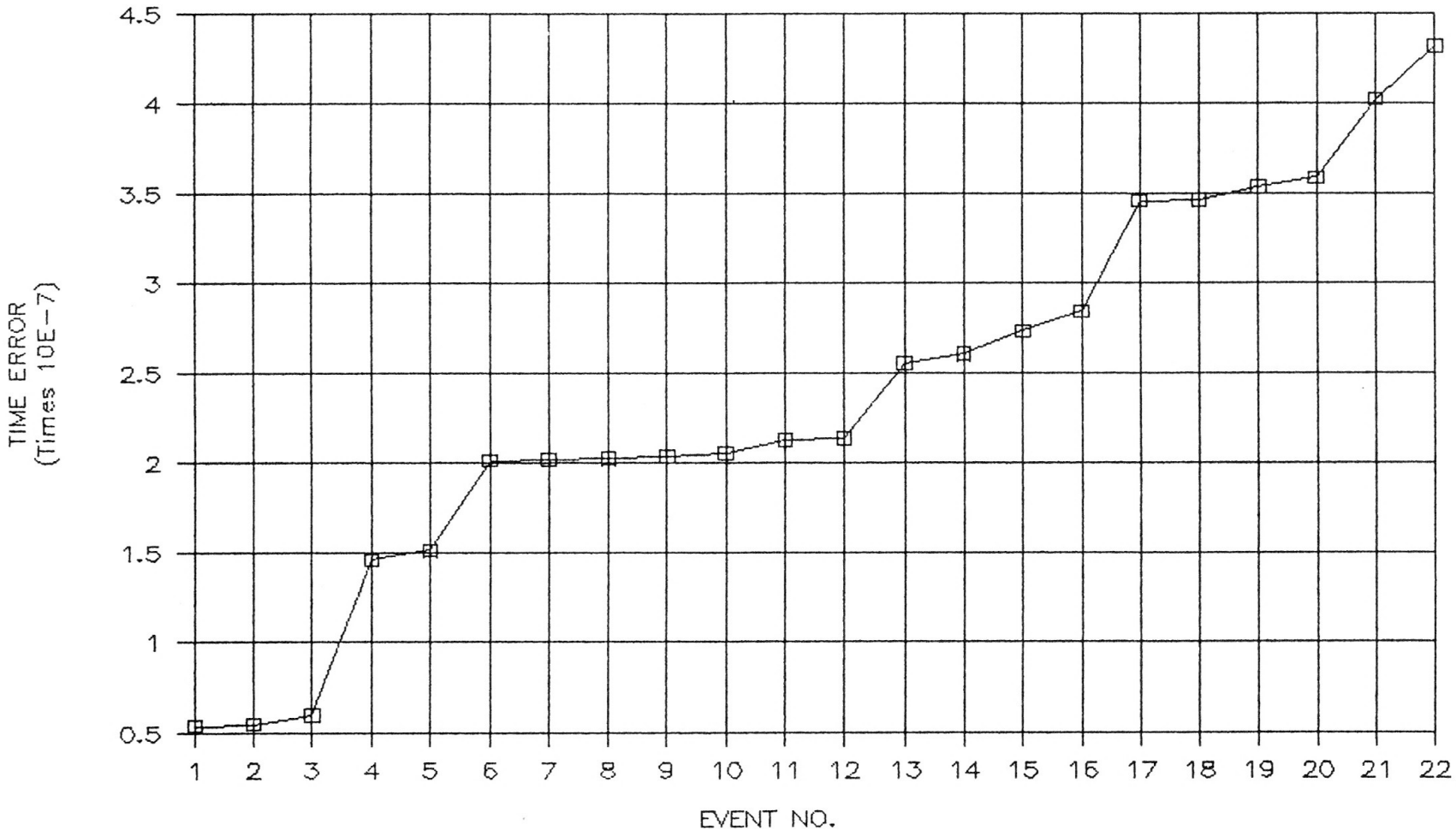
ACCUM. TIME ERROR, AGING

Ball Efratom Division



ACCUM. TIME ERROR, LAST CAL

Ball Efratom Division



FIGHTER AIRCRAFT 4-HOUR MISSION PROFILE

TIME ERROR ANALYSIS EMXO QUARTZ CRYSTAL OSCILLATOR

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
EMXO QUARTZ CRYSTAL OSC.

PART-1-

12-8-91,HUGO
EMXOFTR.WK1

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	MISSION ACTIONS	LINEAR ACCEL. in G's	ACCEL TIME (SEC)	ACCUMUL TIME ERROR (SEC)
	PARAMETER					ACCEL.
	EXPECTED FREQ					1.00E-09
	OFFSET OF OSC					per G
	MODEL EMXO Qz					
	TIME/FREQ HANDBOOK					SECTION 4
	NOTES:					NOTE-1-
1	0-1,800	1800	GROUND	0	0	0.00E+00
2	1,800-1,830	30	CLIMB	1.5	30	4.50E-08
3	1,830-2,010	180	CLIMB	1.5	30	9.00E-08
4	2,010-4,860	2850	WUTx6	2	180	4.50E-07
5	4,860-5,040	180	CLIMB	1.5	30	4.95E-07
6	5,040-6,700	1660	WUTx1	2.5	45	6.08E-07
7	6,700-6,730	30	DECEL	-1.5	30	5.63E-07
8	6,730-6,760	30	DECEL	-1.5	30	5.18E-07
9	6,760-6,790	30	DECEL	-1	30	4.88E-07
10	6,790-6,850	60	DECEL	-1	60	4.28E-07
11	6,850-7,090	240	LEVEL	0	0	4.28E-07
12	7,090-7,120	30	DECEL	-1.5	30	3.83E-07
13	7,120-8,520	1400	LEVEL	0	0	3.83E-07
14	8,520-8,700	180	DECEL	-1.5	30	3.38E-07
15	8,700-9,120	420	LEVEL	0	0	3.38E-07
16	9,120-9,480	360	DECEL	-1.5	30	2.93E-07
17	9,480-11,520	2040	LEVEL	0	0	2.93E-07
18	11,520-11,530	10	CLIMB	5.6	10	3.49E-07
19	11,530-11,770	240	LEVEL	0	0	3.49E-07
20	11,770-11,950	180	CLIMB	1.5	30	3.94E-07
21	11,950-13,400	1450	LEVEL	0	0	3.94E-07
22	13,400-14,400	1000	DECEL	-1.5	180	1.24E-07

TOTAL ACCUMULATED TIME ERROR
PER PARAMETER AT LANDING 1.24E-07

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
EMXO QUARTZ CRYSTAL OSC.

PART-2-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	ALTITUDE in FT.	ACCUMUL TIME ERROR (SEC)	TEMP in DEG.C	DELTA TEMP DEG.C	ACCUMUL TIME ERROR (SEC)
	PARAMETER			PRESSURE			TEMP
	EXPECTED FREQ OFFSET OF OSC			2.50E-16 per FT.			3.85E-11 per DEG.C
				1.00E-11			5.00E-09
	MODEL EMXO Qz			40K ft			-55 to 75C
	TIME/FREQ HANDBOOK			SECTION 3			SECTION 3
	NOTES:			NOTE-2-			NOTE-3-
1	0-1,800	1800	0	0.00E+00	50		0.00E+00
2	1,800-1,830	30	4000	3.00E-11	79	29	3.35E-08
3	1,830-2,010	180	25000	1.15E-09	52	2	4.73E-08
4	2,010-4,860	2850	25000	1.90E-08	52	2	2.67E-07
5	4,860-5,040	180	40000	2.08E-08	41	-9	2.04E-07
6	5,040-6,700	1660	40000	3.74E-08	41	-9	-3.70E-07
7	6,700-6,730	30	33000	3.76E-08	49	-1	-3.72E-07
8	6,730-6,760	30	25000	3.78E-08	52	2	-3.69E-07
9	6,760-6,790	30	28000	3.80E-08	50	0	-3.69E-07
10	6,790-6,850	60	25000	3.84E-08	52	2	-3.65E-07
11	6,850-7,090	240	25000	3.99E-08	62	12	-2.54E-07
12	7,090-7,120	30	20000	4.00E-08	65	15	-2.37E-07
13	7,120-8,520	1400	20000	4.70E-08	65	15	5.71E-07
14	8,520-8,700	180	5000	4.73E-08	76	26	7.51E-07
15	8,700-9,120	420	5000	4.78E-08	76	26	1.17E-06
16	9,120-9,480	360	500	4.78E-08	84	34	1.64E-06
17	9,480-11,520	2040	500	4.81E-08	84	34	4.31E-06
18	11,520-11,530	10	5000	4.81E-08	76	26	4.32E-06
19	11,530-11,770	240	5000	4.84E-08	76	26	4.56E-06
20	11,770-11,950	180	25000	4.95E-08	52	2	4.57E-06
21	11,950-13,400	1450	25000	5.86E-08	52	2	4.69E-06
22	13,400-14,400	1000	0	5.86E-08	50	0	4.69E-06
	TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING			5.86E-08			4.69E-06

PRECISION OSCILLATOR TIME
ERROR ANALYSIS, PART-3-
EMXO QUARTZ CRYSTAL OSC.

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	POWER SUPPLY BUS VOLTS	DELTA VOLTS VDC	ACCUMUL TIME ERROR (SEC)	EARTH'S MAG. FIELD DELTA	ACCUMUL TIME ERROR (SEC)
	PARAMETER				P.S.VOLTS		MAG.FIELD
	EXPECTED FREQ OFFSET OF OSC				1.67E-09 per VOLT		5.00E-12 per GAUSS
	MODEL EMXO Qz				1.00E-09 5% DELTA		
	TIME/FREQ HANDBOOK				SECTION 3		SECTION 3
	NOTES:				NOTE-4-		NOTE-5-
1	0-1,800	1800	12.0		0.00E+00	0	0.00E+00
2	1,800-1,830	30	12.6	0.6	3.00E-08	0.132	1.98E-11
3	1,830-2,010	180	12.4	0.4	1.50E-07	0.132	1.39E-10
4	2,010-4,860	2850	12.0	0.0	1.50E-07	0.132	2.02E-09
5	4,860-5,040	180	12.6	0.6	3.30E-07	0.132	2.14E-09
6	5,040-6,700	1660	12.0	0.0	3.30E-07	0.132	3.23E-09
7	6,700-6,730	30	12.0	0.0	3.30E-07	0.132	3.25E-09
8	6,730-6,760	30	12.0	0.0	3.30E-07	0.132	3.27E-09
9	6,760-6,790	30	12.0	0.0	3.30E-07	0.132	3.29E-09
10	6,790-6,850	60	12.0	0.0	3.30E-07	0.132	3.33E-09
11	6,850-7,090	240	12.0	0.0	3.30E-07	0.132	3.49E-09
12	7,090-7,120	30	12.0	0.0	3.30E-07	0.132	3.51E-09
13	7,120-8,520	1400	12.0	0.0	3.30E-07	0.132	4.44E-09
14	8,520-8,700	180	11.4	-0.6	1.50E-07	0.132	4.55E-09
15	8,700-9,120	420	12.0	0.0	1.50E-07	0.132	4.83E-09
16	9,120-9,480	360	11.6	-0.4	-9.00E-08	0.132	5.07E-09
17	9,480-11,520	2040	12.0	0.0	-9.00E-08	0.132	6.42E-09
18	11,520-11,530	10	12.4	0.4	-8.33E-08	0.132	6.42E-09
19	11,530-11,770	240	12.0	0.0	-8.33E-08	0.132	6.58E-09
20	11,770-11,950	180	12.6	0.6	9.67E-08	0.132	6.70E-09
21	11,950-13,400	1450	12.0	0.0	9.67E-08	0.132	7.66E-09
22	13,400-14,400	1000	12.0	0.0	9.67E-08	0.132	8.32E-09
TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING					9.67E-08		8.32E-09

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
EMXO QUARTZ CRYSTAL OSC.

PART-4-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	VIBRATION SPECTRAL DENSITY G-VERT. G SQ/Hz	G-LAT. G SQ/Hz	G-LONG. G SQ/Hz	TOTAL G-rms	ACCUMUL TIME ERROR (SEC)
	PARAMETER						VIBRAT'N
	EXPECTED FREQ OFFSET OF OSC MODEL EMXO Qz					5.5 G-rms	1.9E-11 per SEC. 70 nsec/HR
	TIME/FREQ HANDBOOK						SECTION 4
	NOTES:						NOTE-6-
1	0-1,800	1800	0.0	0.0	0.0	0.0	0.00E+00
2	1,800-1,830	30	1.6	1.7	2.2	5.5	5.83E-10
3	1,830-2,010	180	0.9	0.5	1.5	2.9	2.43E-09
4	2,010-4,860	2850	0.7	0.7	1.3	2.7	2.96E-08
5	4,860-5,040	180	0.9	0.5	1.5	2.9	3.15E-08
6	5,040-6,700	1660	0.7	0.7	1.3	2.7	4.73E-08
7	6,700-6,730	30	0.9	0.3	1.5	2.7	4.76E-08
8	6,730-6,760	30	0.9	0.3	1.5	2.7	4.79E-08
9	6,760-6,790	30	0.7	0.7	1.3	2.7	4.82E-08
10	6,790-6,850	60	0.9	0.3	1.5	2.7	4.88E-08
11	6,850-7,090	240	0.0	0.0	0.0	0.0	4.88E-08
12	7,090-7,120	30	0.9	0.3	1.5	2.7	4.90E-08
13	7,120-8,520	1400	0.0	0.0	0.0	0.0	4.90E-08
14	8,520-8,700	180	1.5	1.6	2.1	5.2	5.24E-08
15	8,700-9,120	420	0.0	0.0	0.0	0.0	5.24E-08
16	9,120-9,480	360	1.5	1.6	2.1	5.2	5.90E-08
17	9,480-11,520	2040	0.0	0.0	0.0	0.0	5.90E-08
18	11,520-11,530	10	1.9	2.1	2.4	6.4	5.92E-08
19	11,530-11,770	240	0.0	0.0	0.0	0.0	5.92E-08
20	11,770-11,950	180	0.7	0.7	1.3	2.7	6.09E-08
21	11,950-13,400	1450	0.0	0.0	0.0	0.0	6.09E-08
22	13,400-14,400	1000	1.5	1.6	2.1	5.2	7.93E-08

TOTAL ACCUMULATED TIME ERROR
PER PARAMETER AT LANDING

7.93E-08

PRECISION OSCILLATOR TIME
ERROR ANALYSIS, PART-5-
EMXO QUARTZ CRYSTAL OSC.

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	ACCUMUL TIME ERROR (SEC)	ACCUMUL TIME ERROR (SEC)	ACCUMUL TIME ERROR (SEC)
	PARAMETER		RETRACE	WARMUP	AGING
	EXPECTED FREQ OFFSET OF OSC MODEL EMXO Qz		1.00E-10 from just environ. RETRACE	1.00E-07 @ 2 MIN. 1.00E-08 @ 4 MIN.	5.79E-15 per SEC. 5.00E-10 per DAY
	TIME/FREQ HANDBOOK		SECTION 3	SECTION 3	SECTION 3
	NOTES:		NOTE-7-	NOTE-8-	NOTE-9-
1	0-1,800	1800	1.80E-07	1.38E-05	9.38E-09
2	1,800-1,830	30	1.83E-07	1.38E-05	9.38E-09
3	1,830-2,010	180	2.01E-07	1.40E-05	9.47E-09
4	2,010-4,860	2850	4.86E-07	1.69E-05	3.30E-08
5	4,860-5,040	180	5.04E-07	1.70E-05	3.31E-08
6	5,040-6,700	1660	6.70E-07	1.87E-05	4.10E-08
7	6,700-6,730	30	6.73E-07	1.87E-05	4.10E-08
8	6,730-6,760	30	6.76E-07	1.88E-05	4.10E-08
9	6,760-6,790	30	6.79E-07	1.88E-05	4.10E-08
10	6,790-6,850	60	6.85E-07	1.89E-05	4.11E-08
11	6,850-7,090	240	7.09E-07	1.91E-05	4.12E-08
12	7,090-7,120	30	7.12E-07	1.91E-05	4.12E-08
13	7,120-8,520	1400	8.52E-07	2.05E-05	4.69E-08
14	8,520-8,700	180	8.70E-07	2.07E-05	4.70E-08
15	8,700-9,120	420	9.12E-07	2.11E-05	4.75E-08
16	9,120-9,480	360	9.48E-07	2.15E-05	4.79E-08
17	9,480-11,520	2040	1.15E-06	2.35E-05	5.99E-08
18	11,520-11,530	10	1.15E-06	2.35E-05	5.99E-08
19	11,530-11,770	240	1.18E-06	2.38E-05	6.01E-08
20	11,770-11,950	180	1.20E-06	2.40E-05	6.02E-08
21	11,950-13,400	1450	1.34E-06	2.54E-05	6.63E-08
22	13,400-14,400	1000	1.44E-06	2.64E-05	6.92E-08
TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING			1.44E-06	2.64E-05	6.92E-08

PRECISION OSCILLATOR TIME
ERROR ANALYSIS,
EMXO QUARTZ CRYSTAL OSC.

PART-6-

TYPICAL 4-HOUR FIGHTER
MISSION PROFILE

EVENT NO.	MISSION TIME (SEC)	DELTA (SEC)	ACCUMUL TIME ERROR (SEC)	COMBINED ENVIRONMT TIME ERROR	COMBINED ENVIRONMT TIME ERROR
	PARAMETER		LAST CAL	WORST	RSS
	EXPECTED FREQ OFFSET OF OSC MODEL EMXO Qz		3.50E-09 per WEEK (no cal for 1 WK)	CASE SCENARIO	(ROOT SUM SQUARED) -TYPICAL-
	TIME/FREQ HANDBOOK		DATA SHEETS		
	NOTES:		NOTE-10-	NOTE-11-	NOTE-12-
1	0-1,800	1800	6.30E-06	2.03E-05	1.52E-05
2	1,800-1,830	30	6.41E-06	2.05E-05	1.52E-05
3	1,830-2,010	180	7.04E-06	2.15E-05	1.57E-05
4	2,010-4,860	2850	1.70E-05	3.53E-05	2.40E-05
5	4,860-5,040	180	1.76E-05	3.63E-05	2.45E-05
6	5,040-6,700	1660	2.35E-05	4.35E-05	3.00E-05
7	6,700-6,730	30	2.36E-05	4.36E-05	3.01E-05
8	6,730-6,760	30	2.37E-05	4.37E-05	3.02E-05
9	6,760-6,790	30	2.38E-05	4.38E-05	3.03E-05
10	6,790-6,850	60	2.40E-05	4.40E-05	3.05E-05
11	6,850-7,090	240	2.48E-05	4.53E-05	3.13E-05
12	7,090-7,120	30	2.49E-05	4.54E-05	3.14E-05
13	7,120-8,520	1400	2.98E-05	5.26E-05	3.62E-05
14	8,520-8,700	180	3.05E-05	5.34E-05	3.68E-05
15	8,700-9,120	420	3.19E-05	5.58E-05	3.83E-05
16	9,120-9,480	360	3.32E-05	5.76E-05	3.96E-05
17	9,480-11,520	2040	4.03E-05	6.97E-05	4.69E-05
18	11,520-11,530	10	4.04E-05	6.98E-05	4.69E-05
19	11,530-11,770	240	4.12E-05	7.11E-05	4.78E-05
20	11,770-11,950	180	4.18E-05	7.22E-05	4.84E-05
21	11,950-13,400	1450	4.69E-05	7.90E-05	5.36E-05
22	13,400-14,400	1000	5.04E-05	8.34E-05	5.71E-05
TOTAL ACCUMULATED TIME ERROR PER PARAMETER AT LANDING			5.04E-05	8.34E-05	5.71E-05

EMXO NOTES

1. Accelleration sensitivity is (1E-9) (±G's) (Event Time).

2. Altitude sensitivity is 1E-11 at 40,000 ft. For simplicity use a linear fit, 1E-11/40,000 ft. = 2.5E-16/ft.

3. Temp coefficient is (5E-9/130) (Temp Delta from 50°C). The temp coefficient is not a linear function, but due to the small range in this analysis, consider it linear.

   ****DEPOT CALIBRATE UNIT AT 50°C AMB. TEMP.****

4. Supply voltage change sensitivity is 1E-9 for a ±5% change from the 12 Vdc Electronic Bus input voltage. So, 1E-9/0.6 Vdc (Delta volts) (Event Time).

   ****DEPOT CALIBRATE UNIT AT 12.0 VDC SUPPLY VOLTAGE****

5. Magnetic field sensitivity is mainly from the earth's field. Use 33% of earth's mag. field (~0.4 gauss) as a constant offset. So, 5E-12 (33% of 0.4 gauss) (Event Time).

6. Vibration sensitivity is from 3 spectral densities added together. Also, 70 nanoSEC/HR has been measured for environments like this. The unit with which this measurement was made had a 2E-9/G class crystal. A ~1E-9/G class crystal in the EMXO will improve the performance. The formula is: (70E-9/3600)(G-rms/5.5)(Event Time).

   ****PERFORMANCE DEPENDS HEAVILY ON THE FREQ. SPECTRUM****

7. Retrace: Since the Qz frequency offset will not return to the original frequency as it is disturbed by environments, a permanent offset of 1E-10 was used. So, 1E-10 (Event Time). This is not the Retrace Spec for oscillator turn-on and off.

8. Warm-up: Assume unit turn-on at start of 30 minute GRD. time, therefore:
   0 to 2 min., ave. offset of 2E-7
   0 to 4 min., ave. offset of 5E-8
   0 to 4 hrs., ave. offset of 1E-9
   All summed is the frequency/time error due to warm-up.

9. The formula used for aging is: time error = 1/2 (drift) (time SQRD). If Event Time is in seconds, convert everything to seconds. So, 1/2 (5E-10/one day's worth of seconds) (Event Time is sec SQRD)

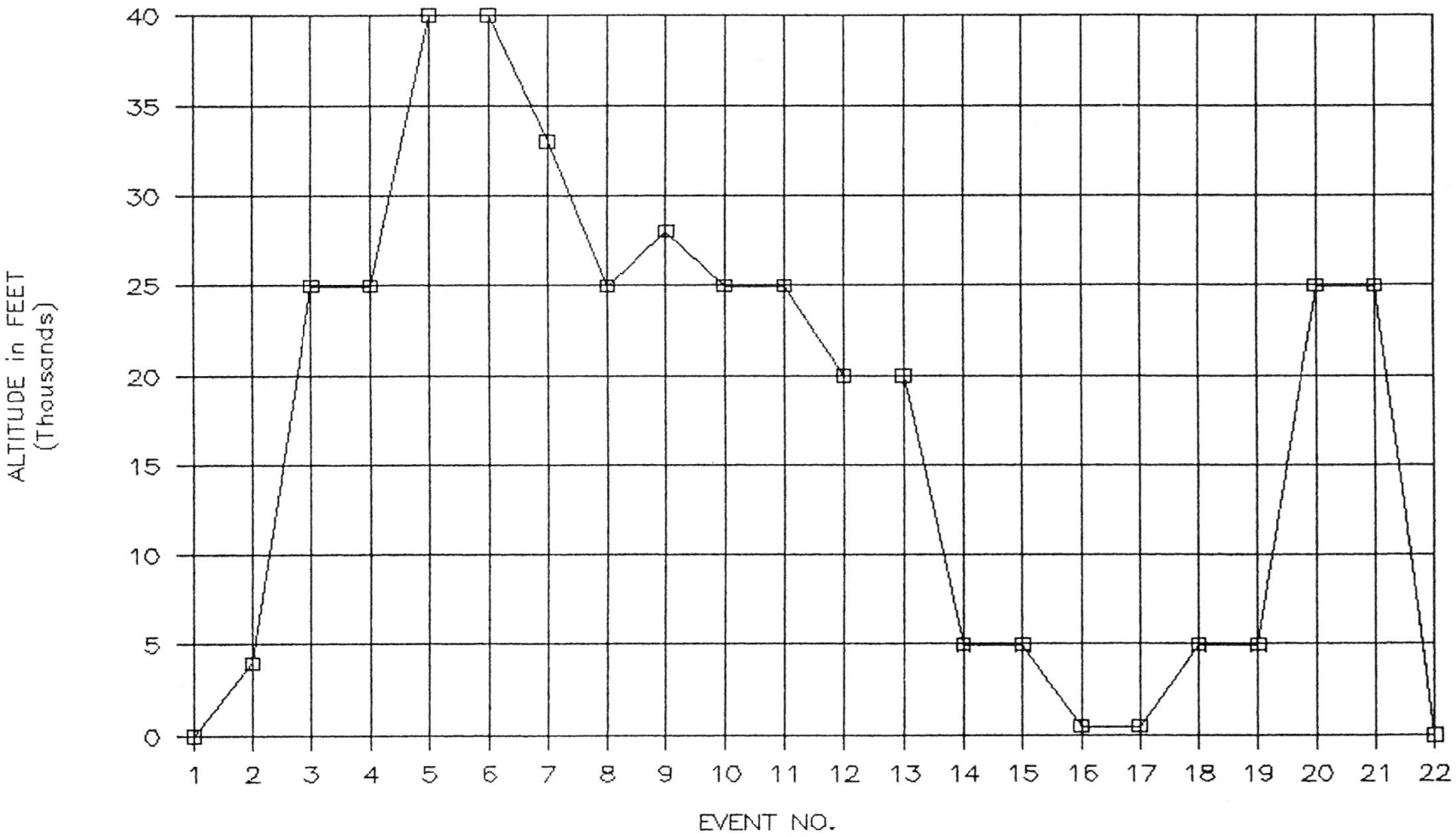
10. A unit not calibrated for one week will have drifted 7(5E-10). Use as a constant offset for the length of mission.

11. This column represents a worst case total with all errors added in an algebraic manner.

12. This represents the most likely error that from experience comes closer to that of the Root Sum Square (RSS) in actual operations. Use this as the typical expected result.

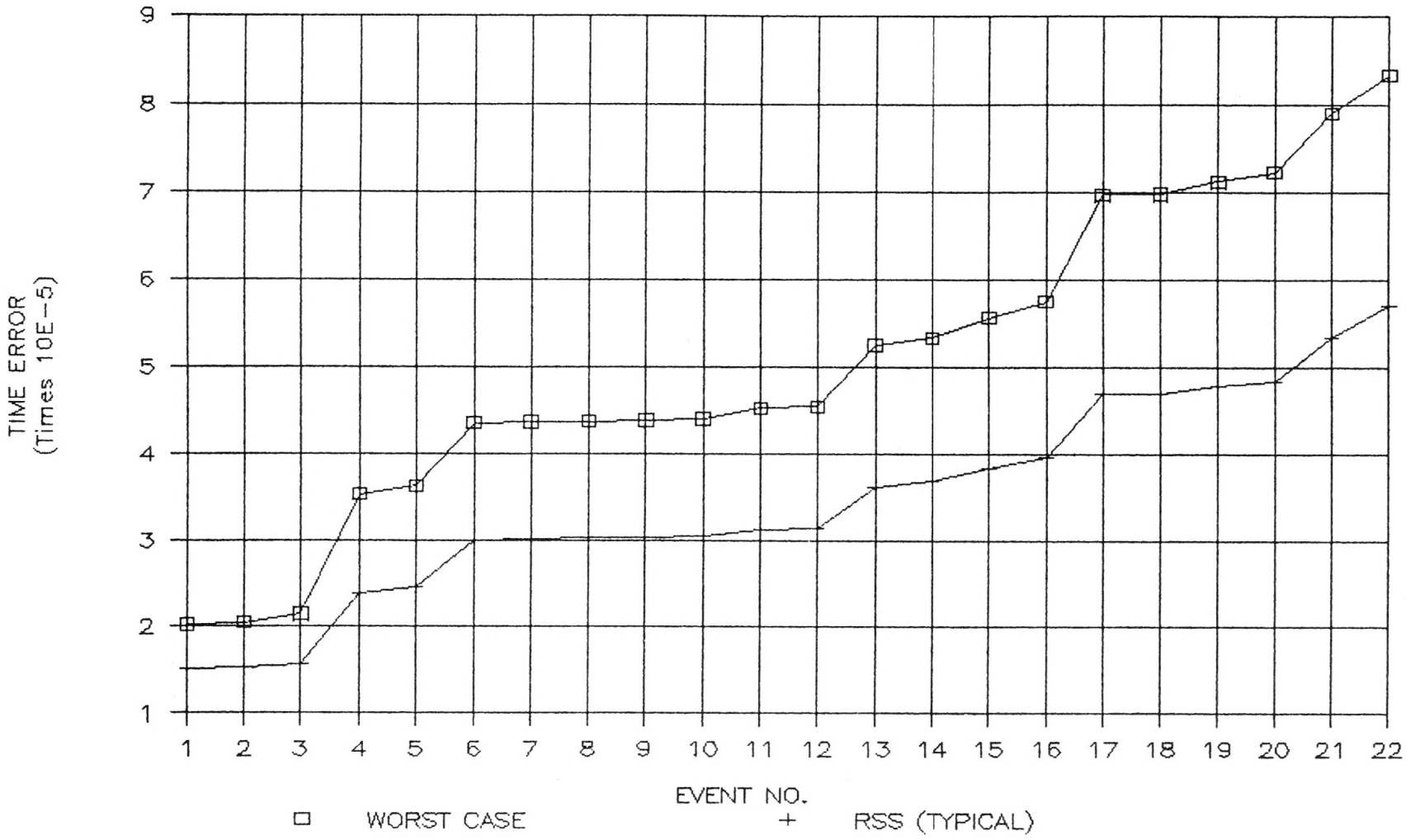
TYPICAL MISSION PROFILE, FIGHTER AIRCRAFT

Ball Efratom Division



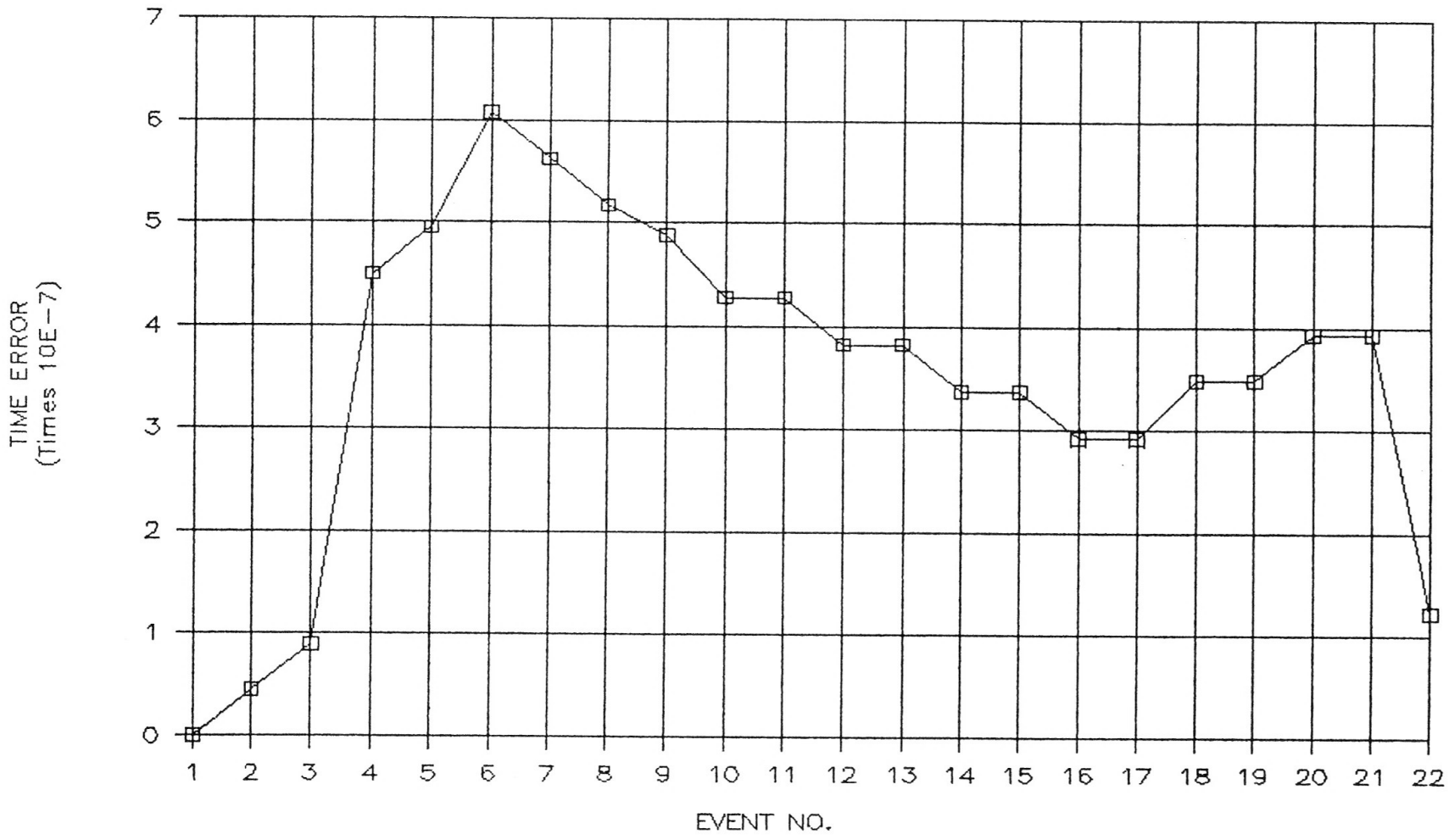
TOTAL ACCUM. TIME ERROR, COMBINED ENVIRONMENTS

Ball Efratom Division



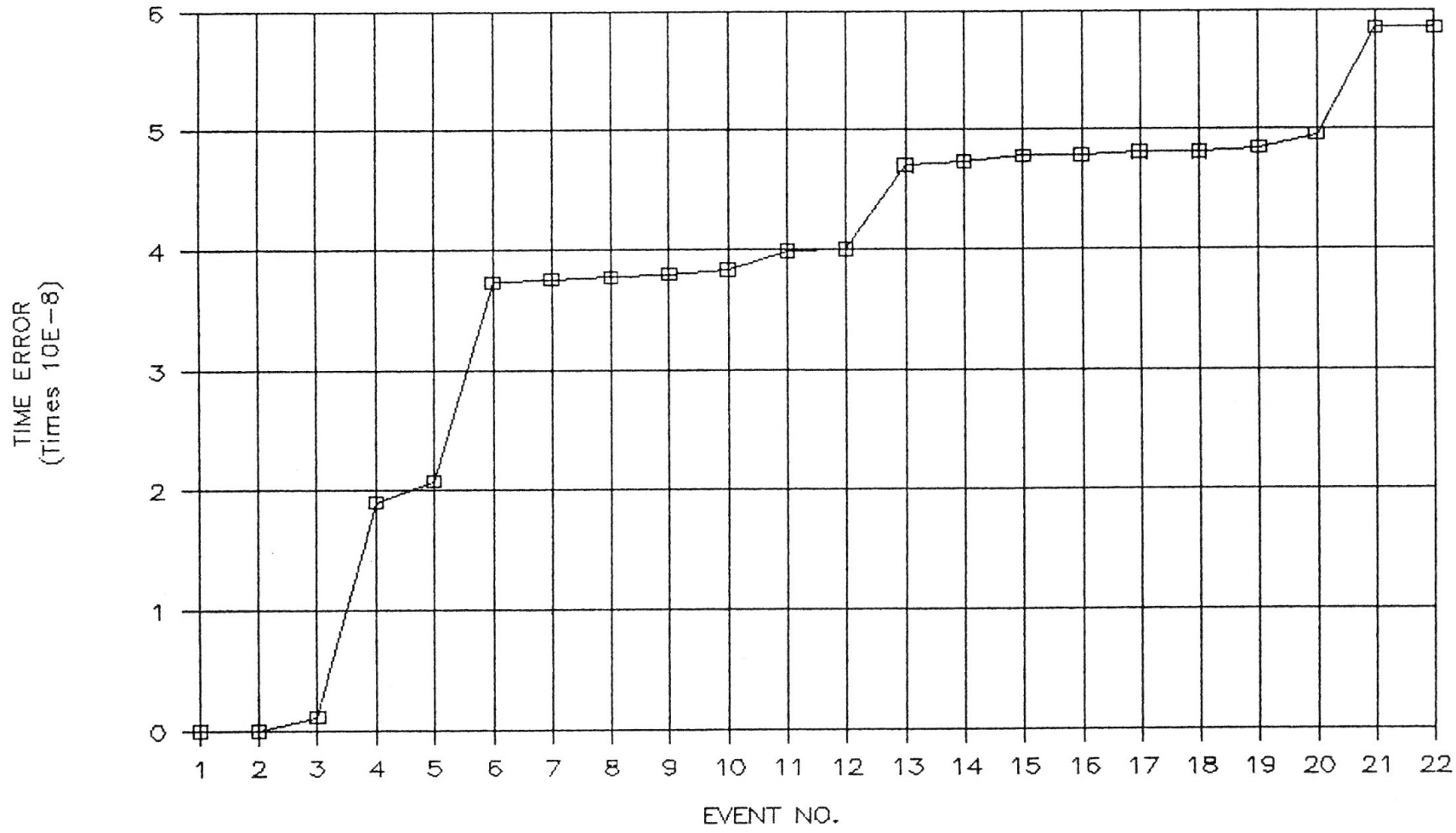
ACCUM. TIME ERROR, ACCELERATION

Ball Efratom Division



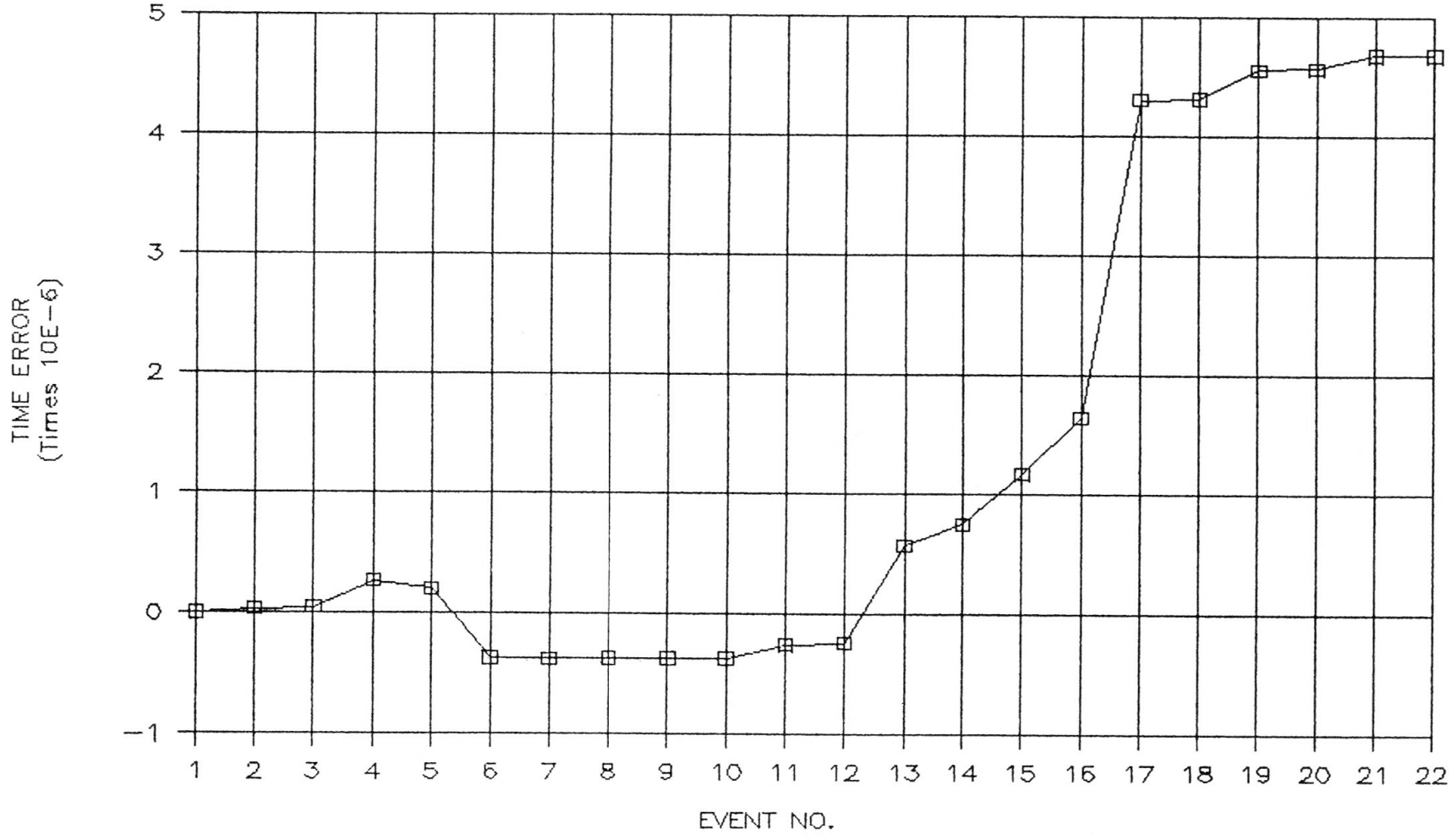
ACCUM. TIME ERROR, PRESSURE

Ball Efratom Division



ACCUM. TIME ERROR, TEMPERATURE

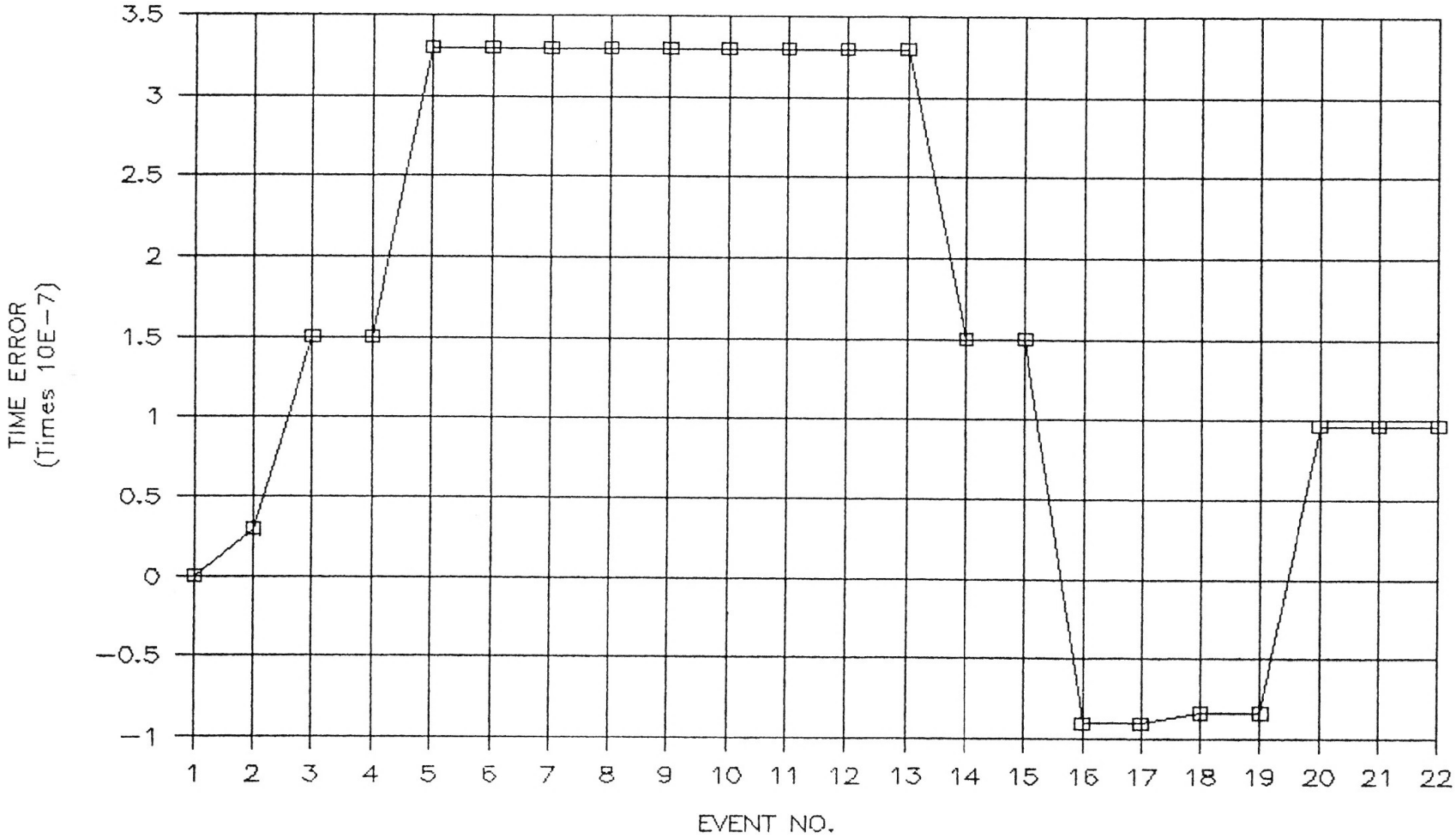
Ball Efratom Division



9.41

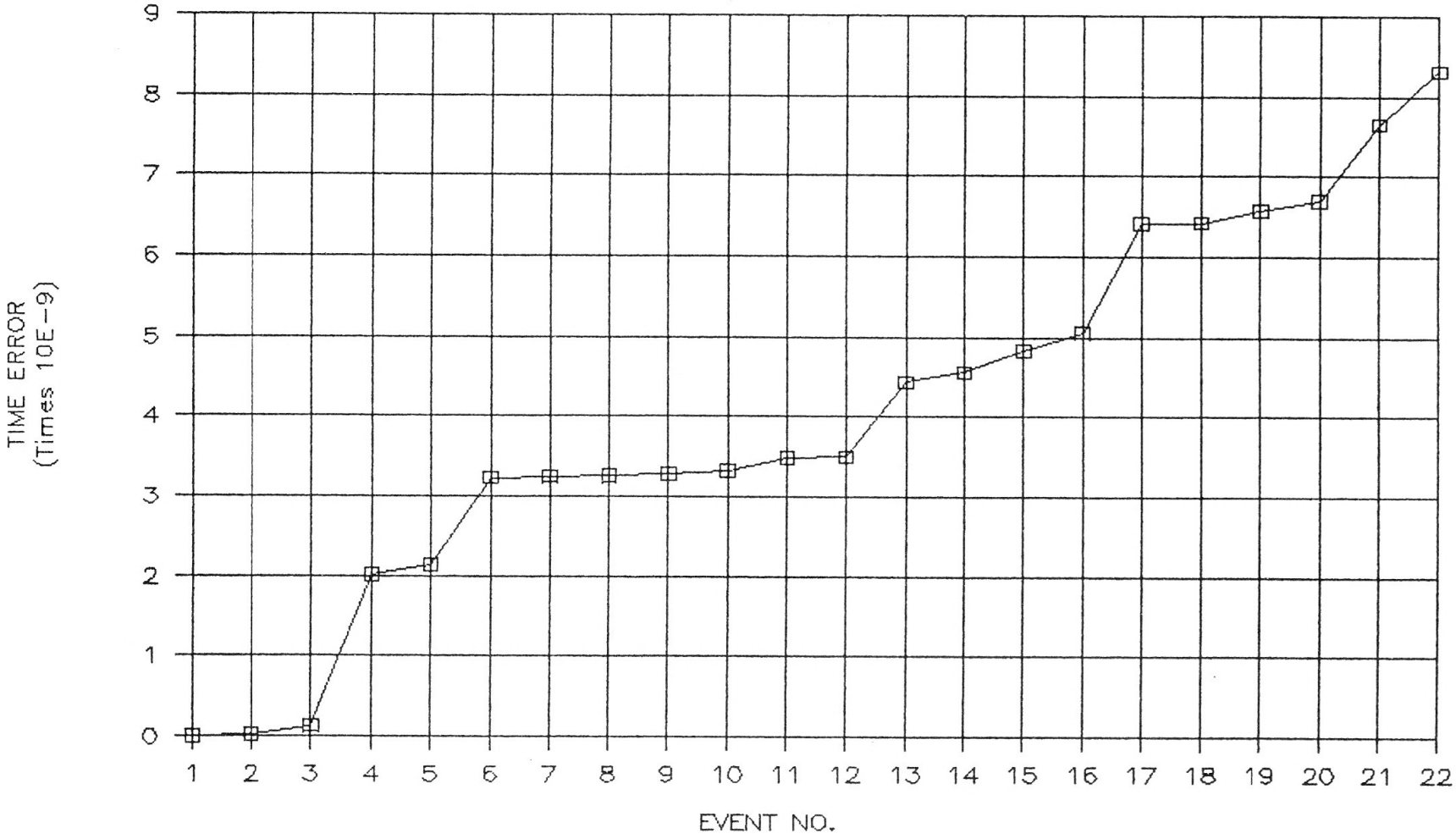
ACCUM. TIME ERROR, VOLTS

Ball Efratom Division



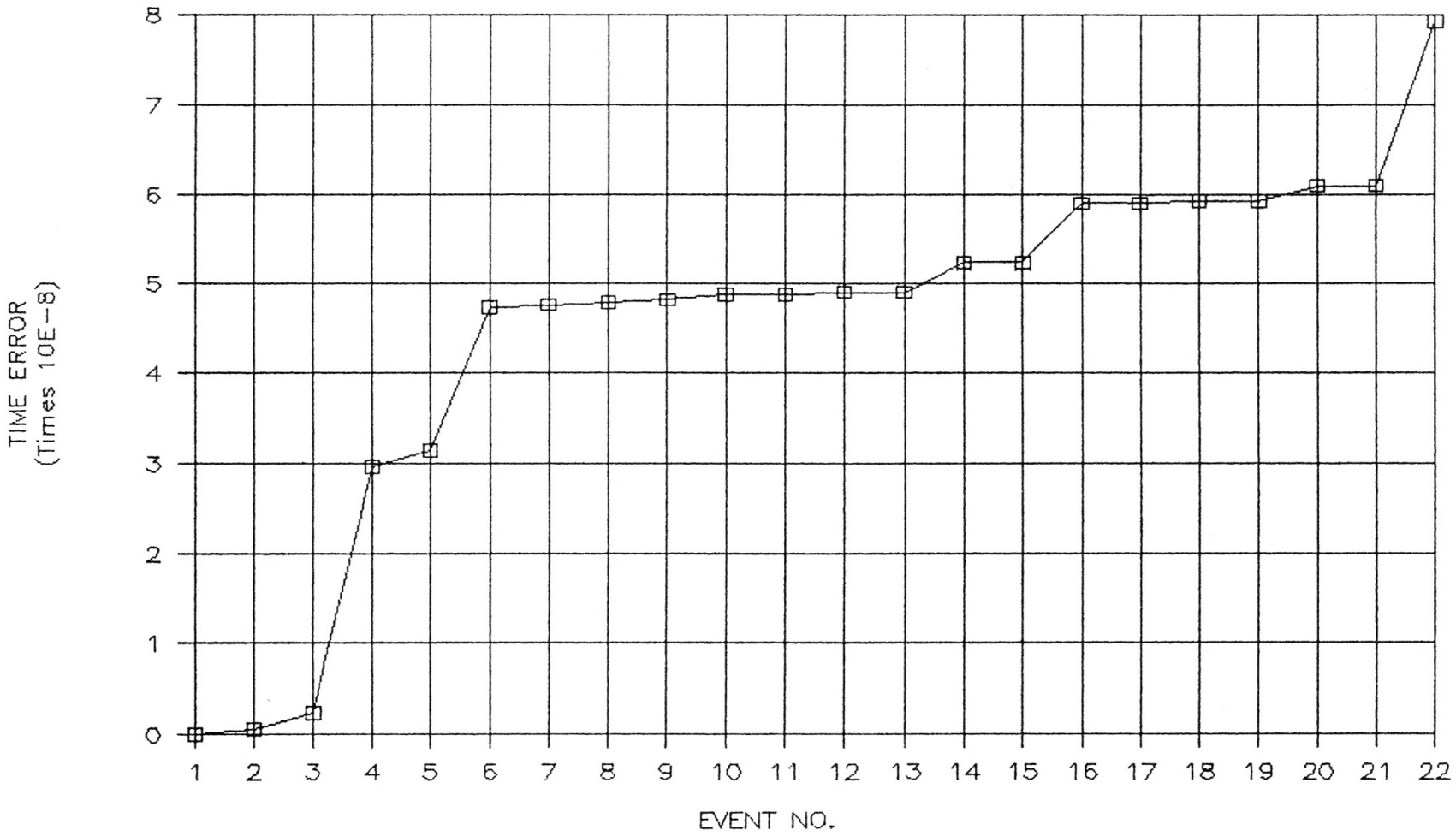
ACCUM. TIME ERROR, MAGNETICS

Ball Efratom Division



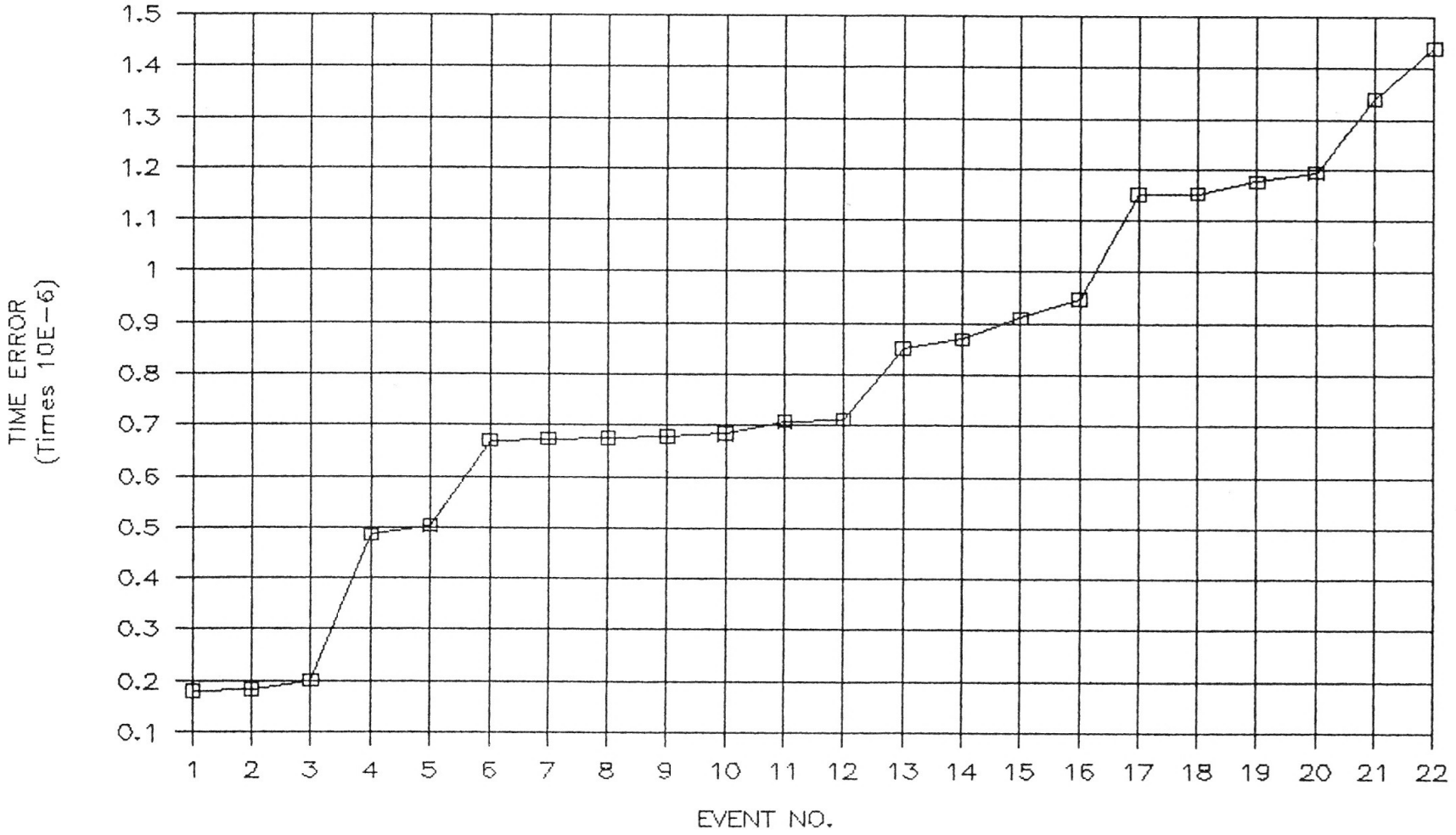
ACCUM. TIME ERROR, VIBRATION

Ball Efratom Division



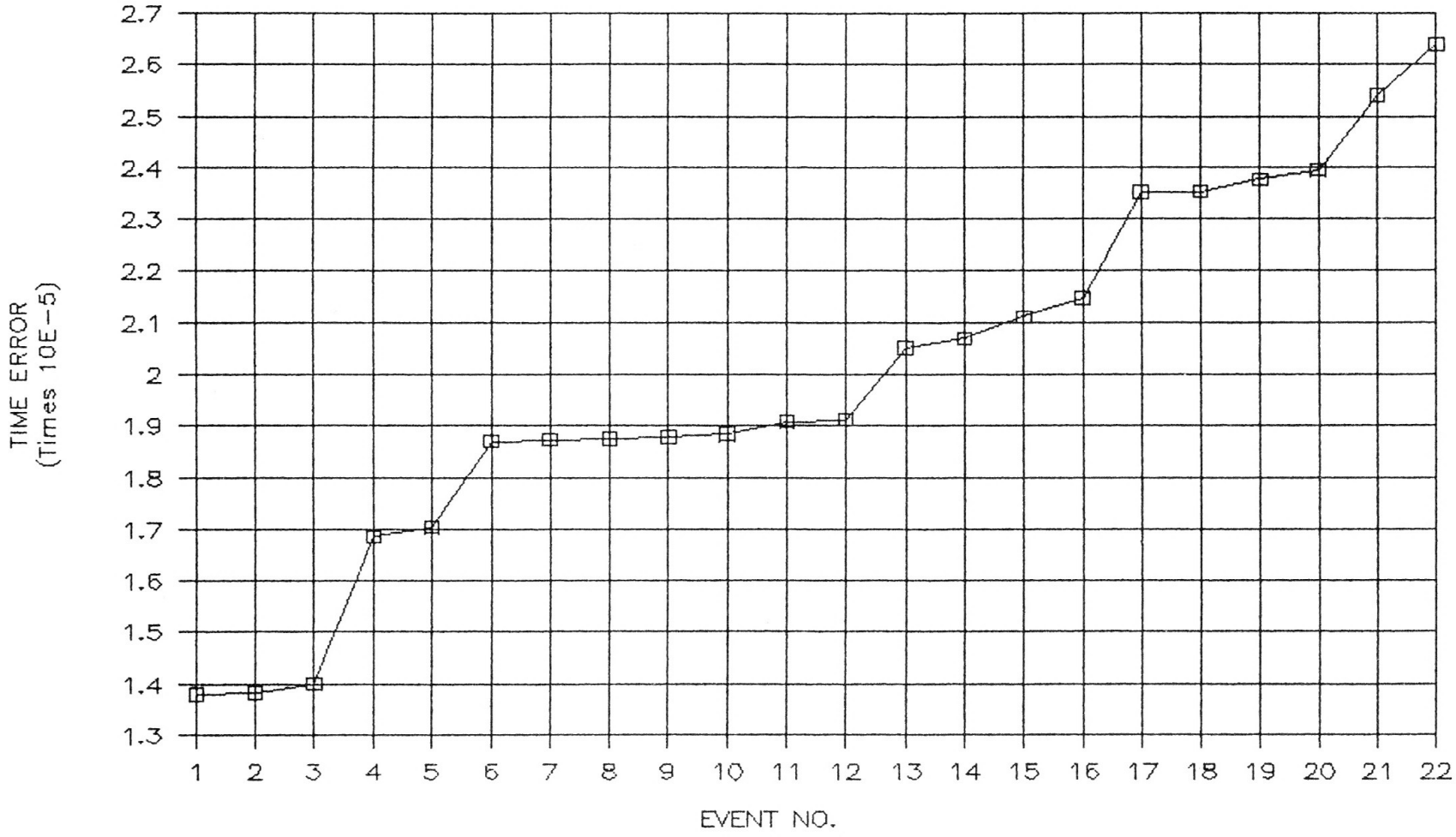
ACCUM. TIME ERROR, RETRACE

Ball Efratom Division



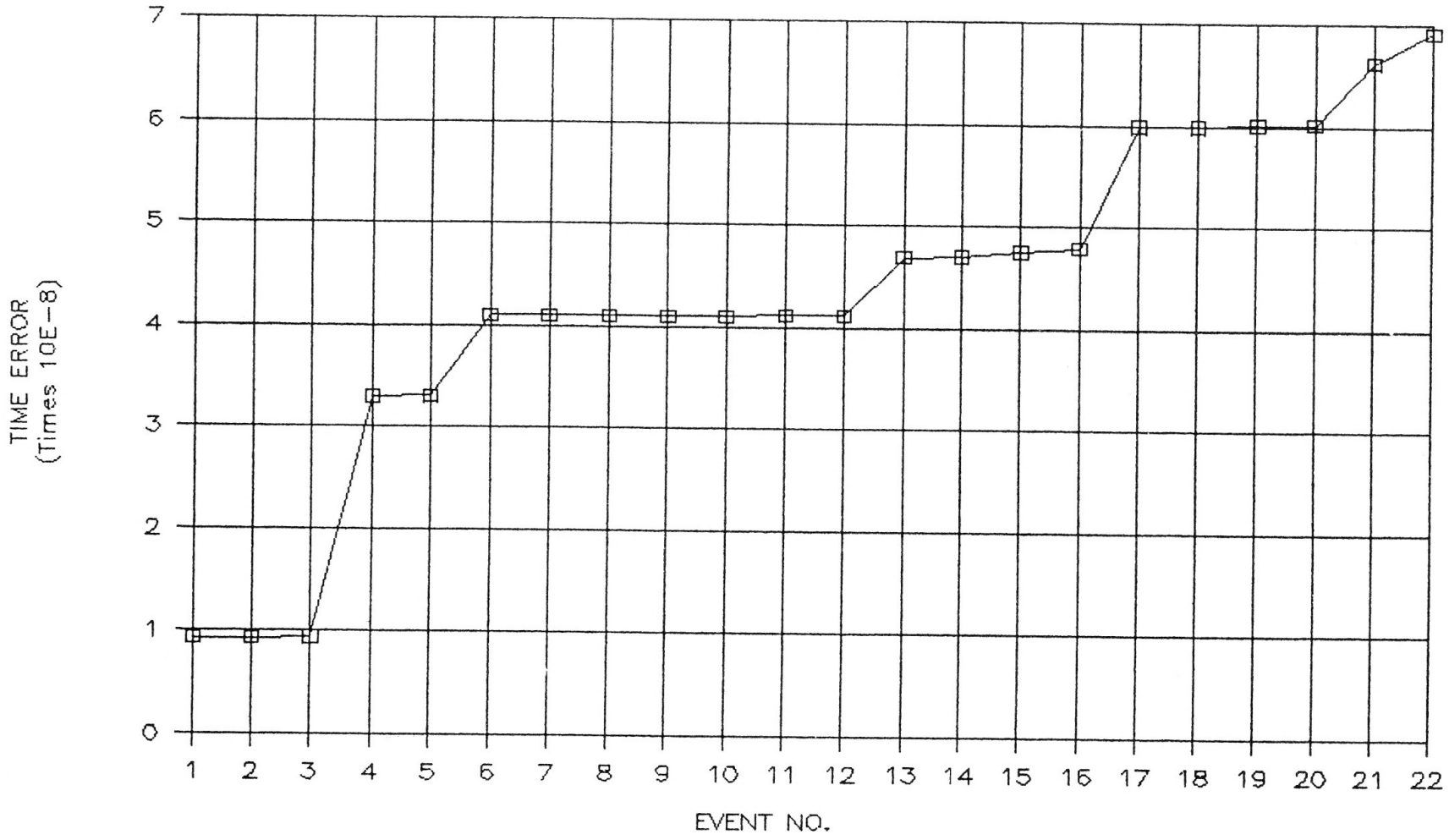
ACCUM. TIME ERROR,WARM-UP

Ball Efratom Division



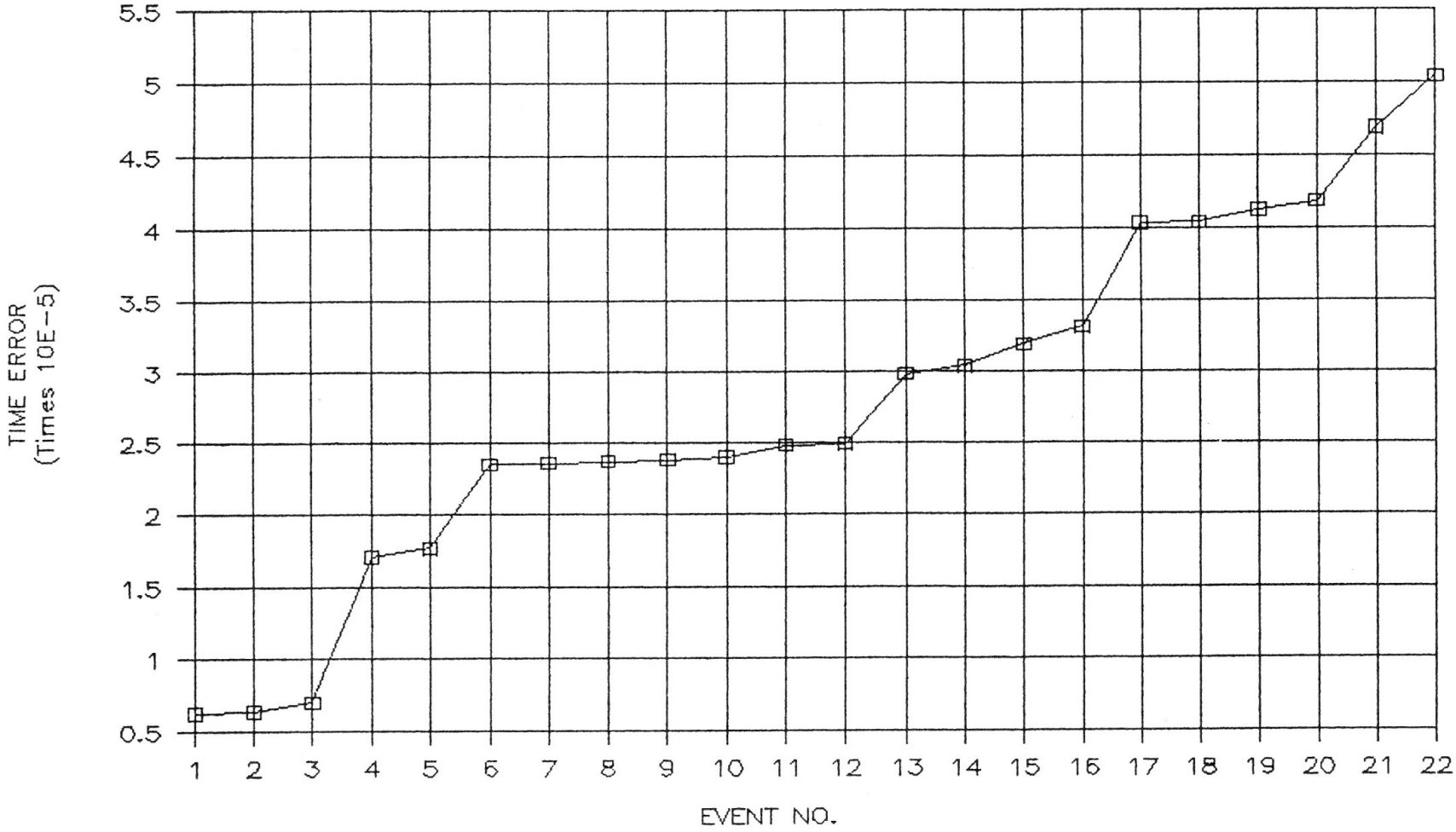
ACCUM. TIME ERROR, AGING

Ball Efratom Division



ACCUM. TIME ERROR, LAST CAL

Ball Efratom Division



EXAMPLE TRUCK MOUNTED Rb ERROR BUDGET ANALYSIS

Ball Efratom Division

This example is an Efratom modular rack of equipment. The frequency source is an MRK Rb oscillator with a special low pressure coefficient cell.

DESCRIPTION	30 DAYS IN WAREHOUSE	2 DAYS TRUCK TRANSPORTATION (No Env. Control)	180 DAYS TRUCK STATIONARY (With Environ. Control)	TOTAL 212 DAYS
DRIFT: 1×10^{-11}/mo.; 3.3×10^{-13}/day	-	-		(1) 0.640 ms
AMBIENT TEMP. ENVIRONMENT	4°C to 38°C	-5°C to 55°C	4°C to 30°C for offset calcul. 15°C to 30°C Ops range	
$\Delta f/f$ FOR THIS TEMP RANGE:	20°C to 40°C 1×10^{-11} 0 to 20°C 2×10^{-11}	-5°C to 55°C $\sim 5 \times 10^{-11}$	0°C to 15°C 1.5×10^{-11} 15°C to 30°C 0.75×10^{-11}	
TEMP-K Δt	0.026 ms + 0.052 ms	0.009 ms	0.233 ms (3) + 0.117 ms	(2) 0.437 ms
MAG. FIELD	No Effect - (Cal. in warehouse)	Averages out.	(4) 4×10^{-12} 0.062 ms	(2) 0.062 ms

(Continued)

EXAMPLE TRUCK MOUNTED Rb ERROR BUDGET ANALYSIS (Continued)

Ball Efratom Division

INITIAL FREQ. SETTING	Calibration to: $\pm 3 \times 10^{-12}$	-	-	0.054 ms
INITIAL TIME SYNC ERROR	0.001 ms	-	-	0.001 ms
ALTITUDE- SEA LEVEL TO 40K FT.	-	-	1×10^{-12} (5)	(2) 0.016 ms
SUPPLY VOLTAGE CHANGE	-	-	-	(6) (2) -0-
VIBRATION	-	(7) 70 µs/hr. 0.004 ms		0.004 ms
TOTAL ERROR				1.214 ms
RSS-TOTAL ERROR				0.780 ms

EXAMPLE TRUCK MOUNTED Rb ERROR BUDGET ANALYSIS (Continued)

NOTES:

1. Time error due to drift $\Delta T_D = 1/2\ at^2$

   a = aging rate of 3.3E-13 x 86400 sec.
   t = no. of days

2. Temp. coefficient, magnetic field, altitude, and supply voltage change effects are all linear functions, so:

   ΔT = x, y, z coefficient x time in seconds

3. For this 180 day phase, the temp-range considers that calibration took place at low temp. in the 30 day warehouse phase.

4. Assume maximum offset of 4E-12 for the worst orientation in the earth magnetic field of about 0.4 gauss.

5. Assume maximum offset due to altitude pressure changes using new low-pressure coefficient cell.

6. No effect from supply voltage changes due to an additional regulator in the MRK module.

7. From test data under fighter aircraft environments that appear to be worse than the truck transport environment.

APPLICATION TOOLS

SYSTEMS DESIGN CONSIDERATIONS

Since the one-way ranging systems and complex spread spectrum systems are only as good as the precision oscillator performance, it is recommended that it become one of the major systems design considerations right from the start.

Since performances described herein are state-of-the-art, any last minute lack of systems performance cannot usually be compensated for by a better precision oscillator. For this reason, the location of this device in the system should be in an area that is as benign as possible, especially with respect to temperature changes. Good oscillator location in the system, which reduces the effects of various environments, will result in major performance improvements.

CHOOSING THE OSCILLATOR BEST SUITED FOR THE JOB

A comparison is presented of four oscillator technologies giving their advantages and disadvantages. For the quartz crystal oscillator, a high performance OCXO is used for comparison; for the rubidium oscillator, the Efratom miniature devices; for cesium, the available 19" rack devices; for hydrogen maser, the 19" rack passive device manufactured by the Soviet Union.

In the following tables, the numbers 1-, 2-, 3-, etc., mean 1st choice, 2nd choice, etc., when in the advantage column. When in the disadvantage column, the numbers still mean 3rd, 4th choice, but imply an unfavorable parameter for the oscillator type listed.

To summarize these figures, consider the following:

For the quartz crystal oscillator, the advantages are low volume, weight, and power. There appear to be cost advantages for the hardware, but when coupled with the calibration intervals which are much more frequent than for atomic oscillators, the cost advantages over a rubidium approach are questionable.

For systems where low volume, weight and power are mandatory, and where aging and retrace disadvantages can be tolerated, the quartz oscillator is the proper choice. The choice, however, suffers if hostile environments are mandatory.

For the rubidium oscillator, the advantages are low volume, low weight for an atomic class oscillator, medium power, and extremely fast warm-up. These, coupled with good performance in a hostile environment, make the rubidium oscillator the first choice for highly mobile and tactical systems. Other than the aging, which is not present in the cesium oscillator, the rubidium oscillator has no major disadvantages.

For the cesium oscillator, the advantages are long-term stability and a consistent source of frequency that requires no calibration. It has medium tolerance to a hostile environment.The larger size and weight and the higher power and cost make the cesium oscillator more useful in stationary and benign environmental applications, more as a reference to which other, less stable oscillators would periodically be checked. Where space, power, and dollars are available, the cesium oscillator is the proper choice, especially for ships, submarines, large aircraft, ground stations and laboratories.

For the passive hydrogen maser oscillator, the advantages are extremely high stability from the short term of sub-seconds to days, weeks and months; expected to out-perform the best cesium oscillator available, being about equal to cesium in the yearly time frame. Due to its larger size, weight, and power, and its lack of tolerance of a hostile, changing environment, this oscillator is definitely more oriented toward a stationary environment. The passive hydrogen maser oscillator is the proper choice as the super frequency reference for ships, submarines, ground stations and laboratories, and where standard or high-performance option cesiums are in use, except possibly in large aircraft, for which cesium might still be the better choice.

OSCILLATOR SELECTION GUIDELINES

Ball Efratom Division

GENERAL PARAMETERS	ADVANTAGES	DISADVANTAGES
SIZE	1-XTAL, 2-RB	3-CS, 4-HM
WEIGHT	1-XTAL, 2-RB	3-CS, 4-HM
POWER	1-XTAL, 2-RB	3-CS, 4-HM
COST OF OSCILLATOR HARDWARE	1-XTAL, 2-RB	3-CS, 4-HM
LIFE CYCLE CONSIDERATIONS		
CALIBRATION INTERVAL	1-CS, 2-HM, 3-RB	4-XTAL
SERVICING	1-XTAL, 2-RB, 3-CS	4-HM
RELIABILITY	1-XTAL, 2-RB, 3-CS	4-HM
AVAILABILITY		
NO. OF COMPANIES	1-XTAL, 2-CS	3-RB, 4-HM
DELIVERY TIME	XTAL, RB, CS - SAME	4-HM
EXPERIENCE IN FIELD (IN QUANTITIES)	1-XTAL, 2-RB, 3CS	4-HM

OSCILLATOR SELECTION GUIDELINES (CONTINUED)

Ball Efratom Division

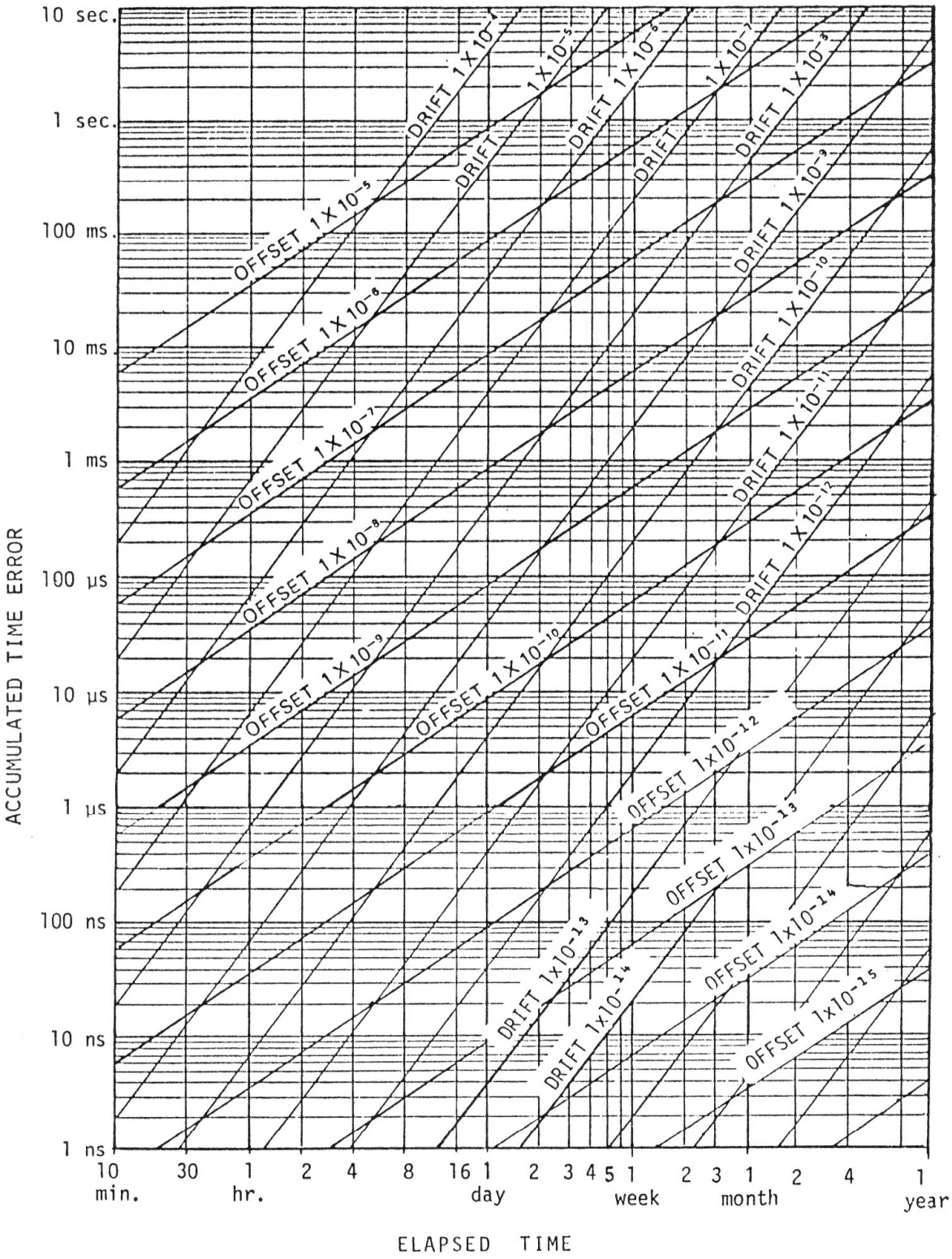
PERFORMANCE	ADVANTAGES	DISADVANTAGES
WARM-UP TIME (TO PARTS IN 10^{10})	1-RB	2-CS, 3-XTAL, 4-HM
SHORT TERM STABILITY		
(τ = 1 TO 10 SEC)	1-HM, 2-XTAL, 3-RB	4-CS
(τ = 10 TO 100 SEC)	1-HM, 2-RB, 3-XTAL	4-CS
LONG TERM STABILITY (τ = 1 DAY TO 1 WEEK)	1-HM, 2-CS, 3-RB	4-XTAL
ACCURACY/AGING PER YEAR	1-HM, 2-CS	3-RB, 4-XTAL
RETRACE	1-HM, 2-CS, 3-RB	4-XTAL
PHASE NOISE	1-XTAL, 2-HM, 3-RB	4-CS
ENVIRONMENTAL		
TEMPERATURE RANGE	1-XTAL, 2-RB	3-CS, 4-HM
TEMPERATURE COEFFICIENT	1-CS, 2-RB	3-XTAL, 4-HM
STORAGE TEMPERATURE	XTAL, RB, & CS - SAME	4-HM

OSCILLATOR SELECTION GUIDELINES (CONTINUED)

Ball Efratom Division

ENVIRONMENTAL (CONT.)	ADVANTAGES	DISADVANTAGES
ACCELERATION	1-RB, 2-XTAL	3-CS, 4-HM
VIBRATION	1-RB, 2 XTAL	3-CS, 4-HM
SHOCK	1-RB, 2 XTAL	3 CS, 4-HM
MAGNETIC FIELD	1-XTAL, 2-CS	3-RB, 4-HM
PRESSURE	1-XTAL, 2-CS	3-RB, 4-HM
RADIATION	1-CS, 2-RB	3-HM, 4-XTAL
APPLICATION		
TACTICAL MOBILE, GROUND, AIR	1-RB, 2-XTAL	3-CS, 4-HM
SHIPS, SUBS, LARGE AIRCRAFT	1-CS, 2-HM	3-RB, 4-XTAL
GROUND STATIONS, LABS	1-CS, 2-HM	3-RB, 4-XTAL
PORTABLE HARDWARE	1-XTAL, 2-RB	3-CS, 4-HM
SATELLITES	1-XTAL, 2-RB	3-CS, 4-HM

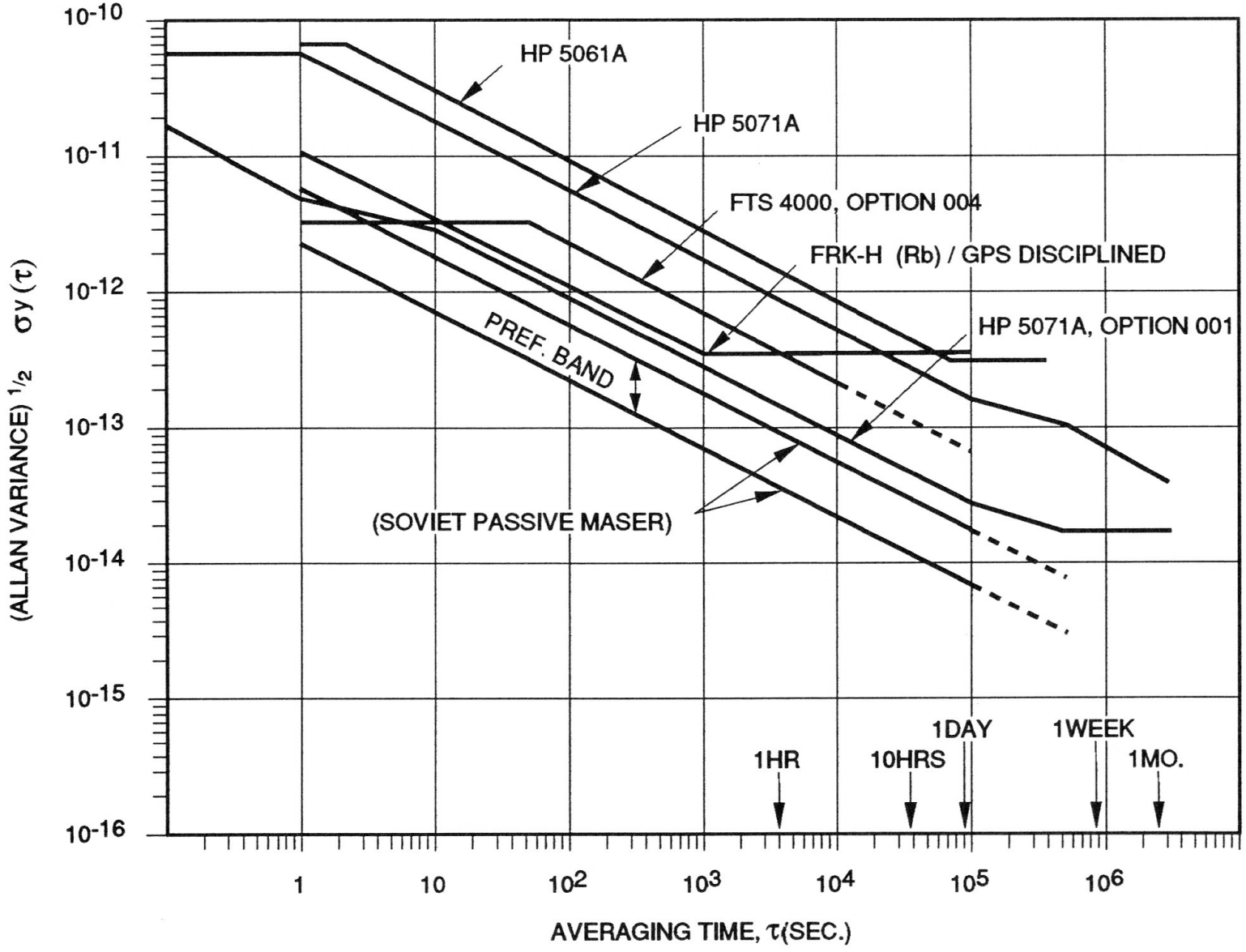
FREQUENCY AGING AND OFFSET vs. TIME ERROR



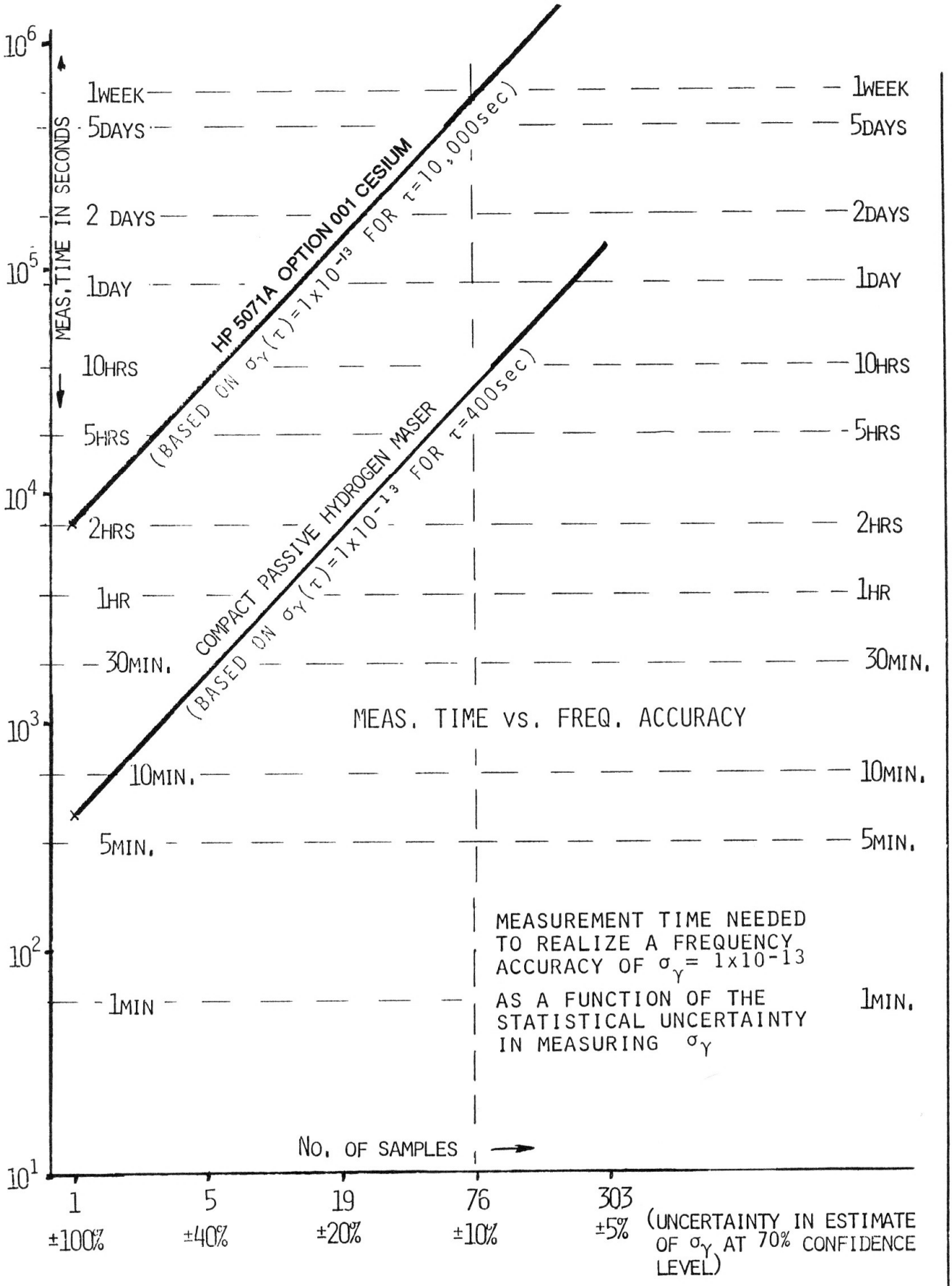
NOTE: AGING LINES REPRESENT "AGING/DAY"
OFFSET LINES ARE INDEPENDENT OF A TIME PERIOD
ADD AGING AND EXPECTED OFFSET FOR A TOTAL TIME ERROR

ALLAN VARIANCE COMPARISON OF CESIUMS AND PASSIVE MASER

Ball Efratom Division



MEASUREMENT TIME vs. FREQUENCY ACCURACY



10

DETAILS OF PRECISION FREQ. SOURCES

Ball Efratom Division

TECHNOLOGIES	GENERAL TECHNOLOGY DOMINATED BY:	SHORT-TERM STAB-1 SEC.	LONG-TERM STAB-1 DAY	FREQUENCY AGING-1 YR	APPROX. QTY. PRICE RANGE
1. QUARTZ CRYSTAL OSC	FEI				
- TCXO		1E-9	4E-8 *	1E-6	$50 - $200
- MCXO		3E-10	2E-9 *	5E-8	$3K - $4K
- OCXO		5E-12	7E-10 *	5E-8	$400 - $2k
- SUPER OCXO (BVA)		5E-13	9E-10 *	2E-8	$2K - $4K
- SPACE QZ		5E-12	1E-10 *	2E-9	$75K - $150K
2. RUBIDIUM OSC	BALL				
- LOW COST COM'L Rb		1E-10	7E-12	5E-10	$3K
- HIGH PERF. Rb		1E-11	3E-13	2E-10	$7K
- LOW COST SPACE Rb		1E-11	3E-13	2E-10	$25K-$50K
- HIGH PERF. SPACE Rb		1E-11	5E-14 ?	2E-11	$250K-$400k
- GPS/Rb-Cs SUBST.		1E-11	1E-12 ?	(NONE)	$20K-$25K
3. CESIUM OSC.	H.P.				
- STD. Cs		6E-11	2E-13	(NONE)	$50K - $55K
- HIGH PERF. Cs		5E-12	3E-14	(NONE)	$60K - $70K
4. HYDROGEN MASER	USSR				
- PASSIVE MASER	(KVARZ)	3E-12 (5E-13)?	3E-14 (1E-14)?	1E-13 (<1E-13)	$70K - $100K
- ACTIVE MASER	USSR + USA MAKERS	4E-13	5E-15	<1E-13	$150K - $450K

ABBREVIATIONS:

TCXO - TEMP. COMPENSATED Qz OSC
MCXO - MICRO PROCESSOR COMPENSATED Qz-OSC
OCXO - OVEN CONTROLLED Qz OSC
(BVA) - FRENCH DEV. SPECIAL Qz STRUCTURE

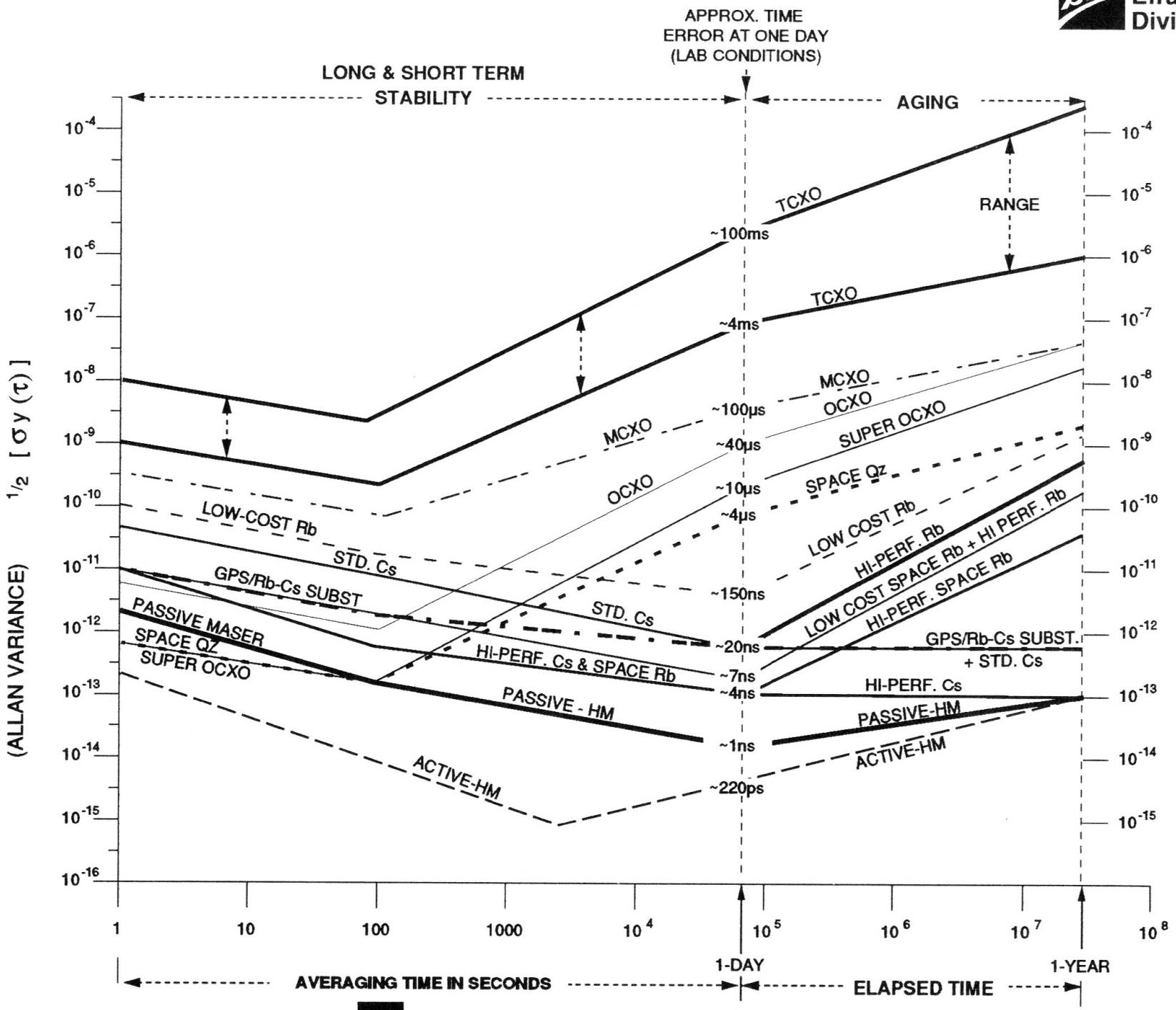
NOTES:

- STABILITIES & AGING ARE APPROX. NUMBERS
- STABILITY AT 1-DAY IS IN LAB CONDITIONS
- EXAMPLE: 1E-11 OF 10 MHz = 0.0001 Hz

* BEST GUESS

DETAILS OF PRECISION FREQ. SOURCES (COMBINED)

Efratom Division



USEFUL TIME AND FREQUENCY RELATIONSHIPS

- Osc. Output Level $dBm = 10 \log \left[\frac{Vrms^2}{50\Omega}\right] \times 1000$ (i.e. 7 dBm = 0.5 Vrms

- Clock Accuracy
  - 1E-8 ~1 milli sec/day error
  - 1E-11 ~1 micro sec/day error
  - 1E-14 ~1 nano sec/day error

- Propagation Delay
  - ~1 nano sec/ft
  - ~5 micro sec/mile
  - ~3.3 micro sec/Km

- Doppler Shift $\frac{\Delta F}{F} = \frac{2V}{C}$
  - V = velocity (meters/sec)
  - C = Speed of Light (meters/sec)

  Doppler Example If V = 4 Km/Hr (which is 1.1 meters/sec), a slow moving tank and X-band radar is F = 10 GHz, then $\frac{\Delta F}{10\ GHz} = \frac{2\ (1.1)}{300 \times 10^6}$ or ~73 Hz

  low phase noise 73 Hz from carrier is necessary in order to see tank

- Time to reach 1 sec time error as function of oscillator error. $t = \sqrt{\frac{2}{a}}$
  - a = aging rate/period of time*
  - *(converted to seconds)

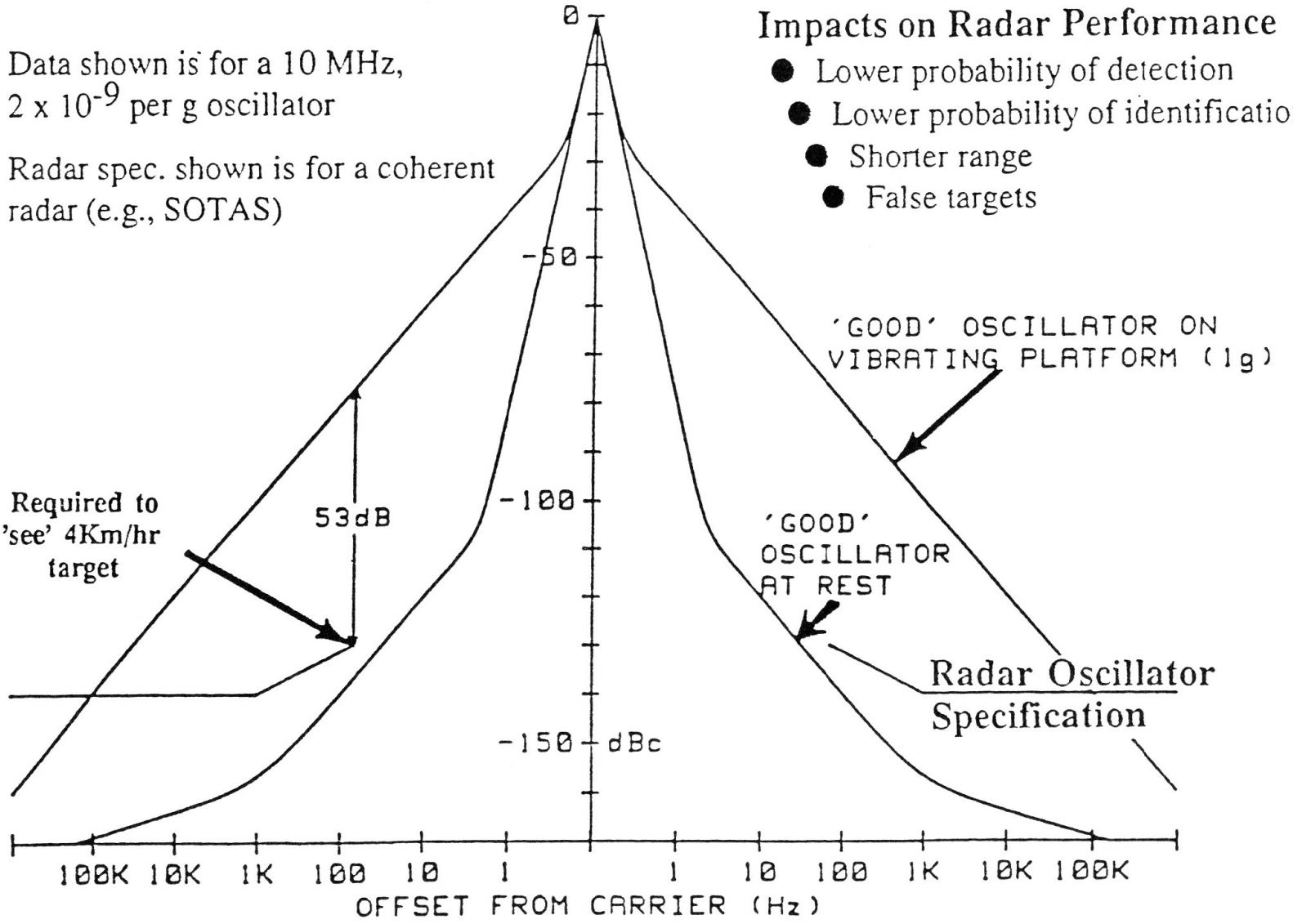
PHASE NOISE DEGRADATION DUE TO VIBRATION

Ball Efratom Division

- Data shown is for a 10 MHz, 2×10^{-9} per g oscillator
- Radar spec. shown is for a coherent radar (e.g., SOTAS)

Impacts on Radar Performance

- Lower probability of detection
- Lower probability of identification
- Shorter range
- False targets

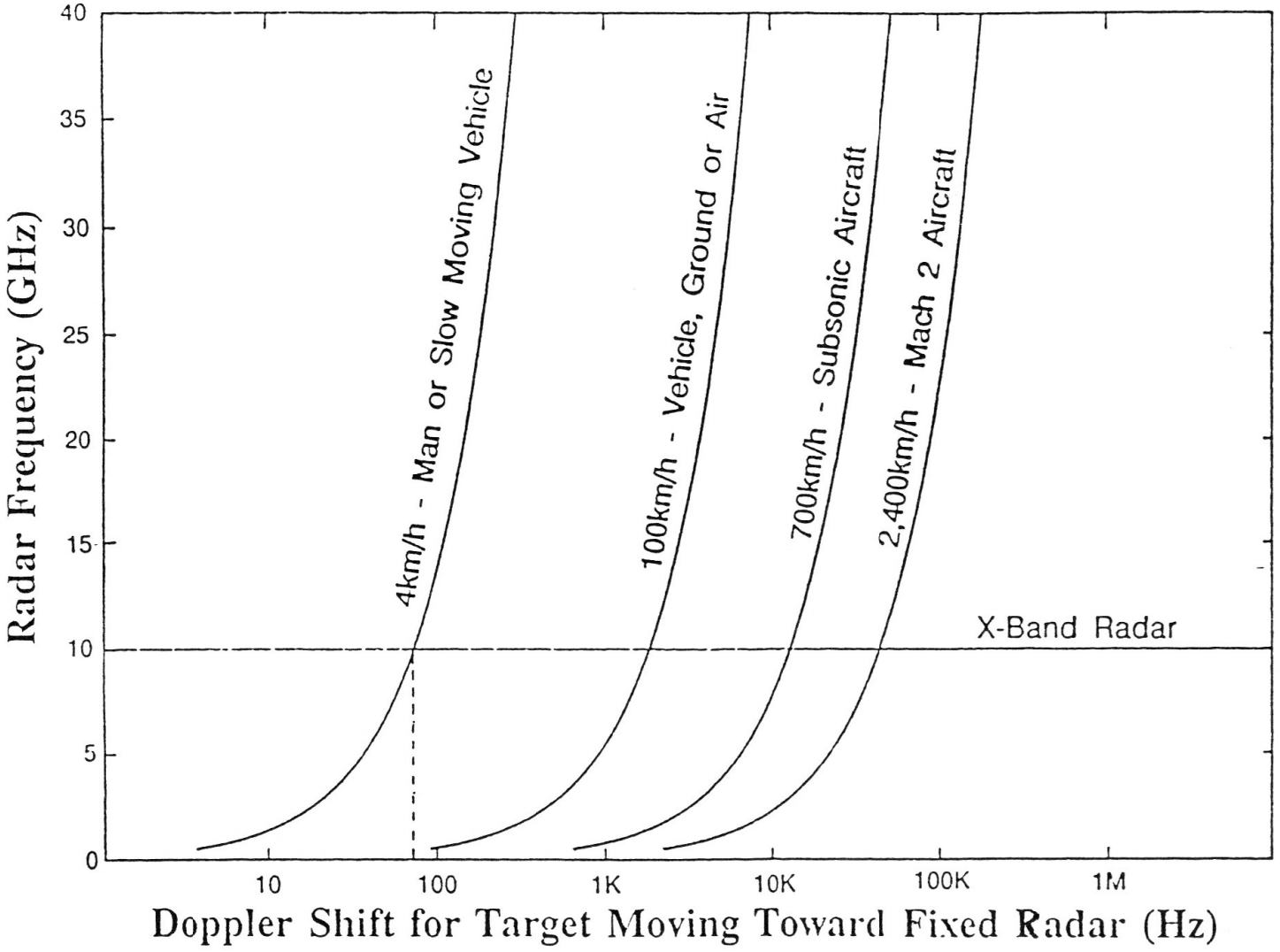


Courtesy of John Vig, Army-LABCOM

DOPPLER SHIFTS

Ball Efratom Division

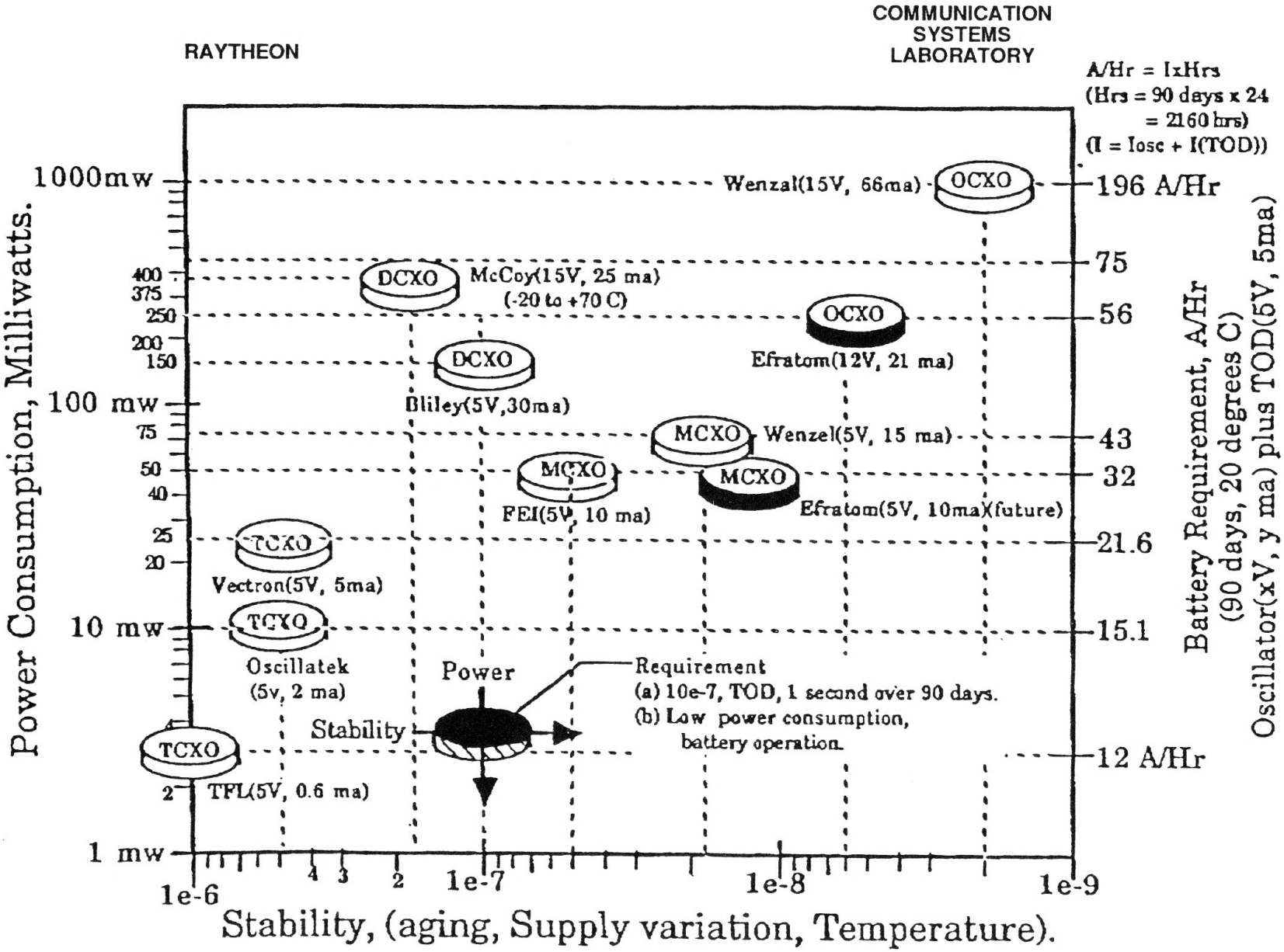
Doppler radars require low-phase-noise oscillators. The velocity of the target and the radar frequency are the primary factors that determine the oscillator noise requirements. For example, to detect slow-moving targets, the noise close to the carrier must be low.



Courtesy of John Vig, Army-LABCOM

QUARTZ OSCILLATORS
STABILITY-vs-POWER CONSUMPTION
(BATTERY REQUIREMENT)

Ball Efratom Division



Atomic Oscillator Theory of Operation

THE GENERALIZED ATOMIC OSCILLATOR[1]

1. Description

An atomic frequency standard is a device the frequency of which is determined by some property of a simple atomic system. The term is not restricted to devices where the frequency derives from neutral atoms, but is also applied to devices based on molecules and ions. The terms "atomic clock" and "atomic oscillator" are often used synonymously. However, sometimes the term "clock" is used to mean a frequency standard connected to a counter - device that provides time as well as frequency.

Atomic frequency standards must be understood in terms of the concepts of quantum mechanics. The properties of simple atomic systems cannot assume arbitrary values. For example, the energies of the bound states of an atomic system are constrained to discrete values called energy levels. When an atomic system changes energy from an excited state to a state with lower energy, it emits a quantity of electromagnetic energy called a photon, the frequency of which is determined by the energy difference between the two states. If the energy of the upper state is E_2 and the energy of the lower state is E_1, the photon frequency is given by Planck's law

$$V = \frac{E_2 - E_1}{h}$$

where h is Planck's constant. The atomic standard produces an output signal the frequency of which is determined by this intrinsic atomic frequency, rather than some property of a bulk material.

The advantages of atomic oscillators all stem from this feature. Intrinsic atomic properties are more easily reproduced than collective properties, endowing atomic frequency standards with the property of accuracy. Atomic systems are easy to isolate from unwanted perturbations, which result in very small sensitivities to temperature, pressure,

[1]The following is taken (in part) from technical report SLCET-TR-91-2, Jan 1991, "Frequency Standards for Communications" by Sam Stein (Ball Corporation) and John Vig Army LABCOM.

and other environmental conditions. The low level of interaction also results in extremely sharp resonance features, and reduces errors due to imperfections in the electronics. All atoms of an element are identical, and atomic properties are time invariant, which makes it possible to build very stable devices. Finally, it is surprisingly easy to measure atomic properties and build practical devices suitable for a wide variety of applications.

Atomic frequency standards are categorized in several ways. Most often, they are referred to by the type of atom: hydrogen, rubidium, or cesium. Actually, these three devices are based on the same type of atomic interaction, but there are great practical differences in their implementation. Some atomic oscillators are active; in this case, the output signal is derived from the radiation emitted by the atom. Others are passive; the atoms are then employed as a discriminator to measure and control the frequency of an electronic oscillator, such as a quartz oscillator. The third classification follows the method of interaction. In atomic beams, the atoms are observed "on the fly"; they pass through the interaction region and are not used again. In contrast, storage devices contain some type of cell that holds the atoms to be observed for a much longer time. In some cases the atoms are recycled.

2. Atomic Spectroscopy

The energy levels of an atom are generally classified according to their physical origin. For example, the principal levels of an atom are associated with the radius of the 'orbit' of an electron about the nucleus. These levels have the largest atomic energy separations. The principal energy levels are subdivided as a result of the quantization of the angular momentum of the atom. The angular momentum due to the motion of a particle, such as an electron, is called "orbital angular momentum". Even when their motion is such that there is no orbital angular momentum, atomic particles may possess an intrinsic angular momentum or spin and a proportional intrinsic magnetic moment. This is another concept unique to quantum mechanics. The principal levels are first divided according to the shape of the electron "orbits." Still finer division occurs as a consequence of the particular orientation of the electron's spin and the spin of the nucleus.

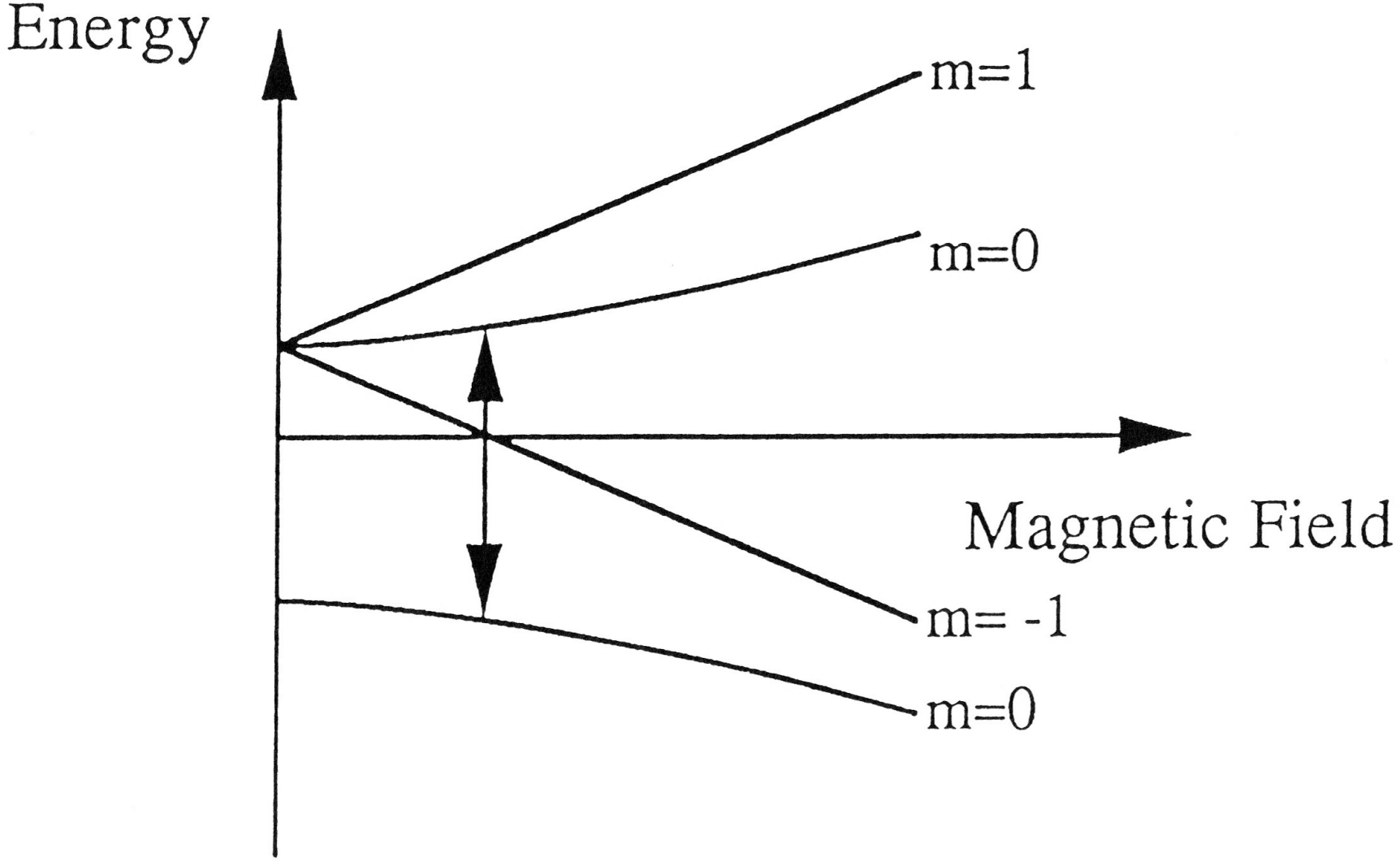
The photons emitted when atoms change states between the principal energy levels are usually in the infrared and higher energy regions of the electromagnetic spectrum. The frequencies of these very energetic photons are too high for practical electronic devices. However, very narrow spectroscopic features associated with principal energy levels

have been obtained in the laboratory and are useful for relative measurements. Atomic frequency standards are feasible because of the splitting of the ground state of the atom. Next lower, in terms of energy, is the fine structure of the atom, which results from the interaction of the spin of the electron with the magnetic field due to the motion of the electron through the nuclear electric field. This structure is thousands of times smaller than the separation of the principal energy levels. Laboratory atomic frequency standards based on fine structure in calcium and magnesium have been built, but the fundamental frequencies of the atomic transitions are higher than 600 GHz, which is very difficult to synthesize.

A finer energy splitting than the spin-orbit coupling is produced by the interaction of the electron and nuclear spins; this is called the hyperfine structure. The ground state of a hydrogen-like atom, for example H, Li, Na, K, Rb, Cs, and singly ionized Be, has a single unpaired electron in a symmetric orbit. In this case, there is no orbital angular momentum and no fine structure. The energy splitting due to the intrinsic magnetic moments of the electron and the nucleus can be a million times smaller than the separation of the principal energy levels. The transition frequencies are quite convenient; 1.4 GHz for hydrogen, 6.8 GHz for rubidium, and 9.2 GHz for cesium. All commercial atomic frequency standards are based on the hyperfine spectroscopy of one of these three atoms.

Because the frequency of such a device is determined by the energy of interaction of a pair of magnetic moments, it is generally altered by any background magnetic field. The hyperfine states are also split into multiple energy levels, called Zeeman sublevels, depending upon the component of the total angular momentum in the direction of an applied magnetic field. Figure 11-1 shows the hyperfine structure of the hydrogen atom in an applied magnetic field. The two states that have no angular momentum component along the direction of the applied field have quadratic dependence of energy on magnetic field for small field values. Thus, the frequency corresponding to a transition between these two levels has very small dependence on the magnetic field and is suitable for use in an atomic frequency standard. Atomic frequency standards utilize a small background magnetic field to allow the selection of the desired magnetic sublevels. The transitions between other levels have too high magnetic field dependence for frequency standard applications - variation in external magnetic fields, such as the earth's field, cannot be shielded sufficiently well to prevent them from perturbing the frequency of the device. The magnetic field dependent transitions are used to manufacture sensitive magnetometers rather than frequency standards.

FIGURE 11-1. MAGNETIC FIELD DEPENDENCE OF THE HYPERFINE DOUBLET IN THE GROUND STATE OF HYDROGEN



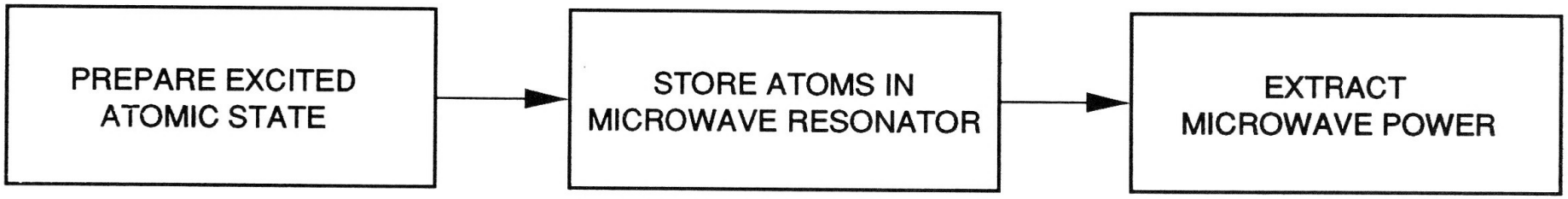
The process of measuring the frequency of atomic transitions is called atomic spectroscopy. Atoms are prepared in one atomic state and then stimulated to change to the second state while some method of observing the transition is employed. The atoms must be stimulated to make the transition because the lifetime of the upper hyperfine state is very long; it is an appreciable fraction of the age of the universe in the case of hydrogen. By applying a field at the transition frequency, atoms can be stimulated to make a rapid transition between hyperfine levels. Typically, the atoms change state in a few milliseconds to one second, during which time they are observed.

Since the hyperfine energy separation is small compared to the thermal energy of atoms in a gas at room temperature, one expects to find nearly equal numbers of atoms in the upper and lower hyperfine states, with slightly more atoms in the lower state. The number of atoms in the lower hyperfine level of room temperature hydrogen gas is 0.01 percent higher than the upper-state population. The number of atoms making transitions from the upper to the lower state and radiating photons is nearly equal to the number making transitions from the lower to the upper state and absorbing photons. Any effects of one process are nearly canceled by the other. In order to observe the process it is necessary to produce a larger discrepancy in the populations of the two levels. After this state selection is performed, it is possible to observe the atomic transition in many ways. In cesium atomic frequency standards, the number of atoms making a transition is measured; whereas in hydrogen masers, the radiation emitted by the atoms is detected.

3. Practical Atomic Spectrometers

Conceptually, the simplest atomic frequency standard is the active oscillator, a block diagram of which is shown in Figure 11-2. Atoms in the upper hyperfine level of the ground state are stored in a microwave resonator. A fraction of the microwaves is coupled out and amplified for the output signal. In order for oscillation to take place, it is necessary for the population of upper state atoms to be increased substantially compared to the lower state atoms, a condition called population inversion. In the presence of microwave fields due to noise, the inversion causes the atoms to emit more power than they absorb. When the gain provided by the atoms exceeds the losses, the microwave fields build up until saturation limits the gain and a steady state condition is reached. Each atom is exposed to a microwave field produced by previously emitting atoms and all atoms are stimulated to emit approximately in phase with one another. The output signal is highly coherent; the dominant short-term noise is white phase noise. The linewidth of the atomic transition is determined by the observation time, which is limited

FIGURE 11-2. BLOCK DIAGRAM OF A GENERAL ACTIVE ATOMIC OSCILLATOR



by processes that destroy either the population inversion or the coherence of the atoms. The active hydrogen maser is an example of the atomic oscillator; it is available commercially and is the primary clock used for radio astronomy. In order to achieve high resolution, radio astronomers use long baseline interferometry - two or more radio telescopes that are widely separated make simultaneous observations, each one using a maser to provide the time base. The clocks must stay coherent to a small fraction of an rf cycle during the observation period. For X-band observations, this implies time errors less than 25 ps for observation times from 15 minutes to several hours.

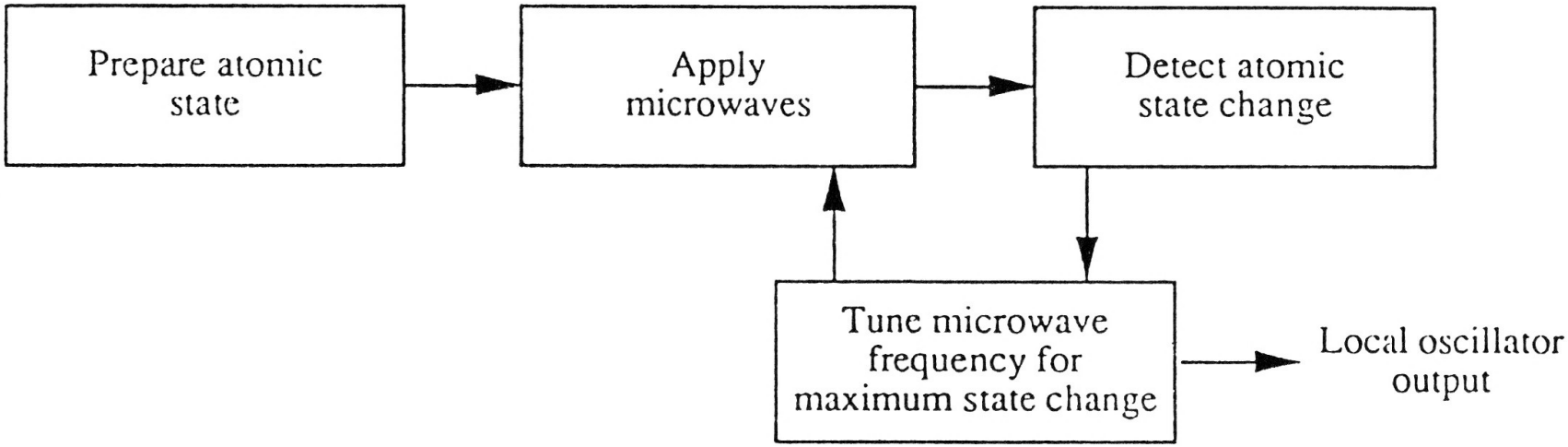
Passive atomic frequency standards are somewhat more complicated than active oscillators; they employ an atomic spectrometer the gain of which is insufficient to sustain oscillation. The spectrometer may even have a net loss. As shown in Figure 11-3, a microwave oscillator stimulates the atomic transitions and a control loop provides feedback to tune the oscillator to the frequency that maximizes the transition rate. The peak transition rate is detected by frequency modulating the microwave signal applied to the atoms. The population of one of the hyperfine states is synchronously detected using the modulating signal as the reference. A signal is obtained proportional to the difference between the microwave carrier frequency and the center of the atomic resonance. The passive approach is used when other constraints make it impossible to achieve self oscillation. This happens, for example, when one tries to approach as closely as possible to the ideal of an isolated atom at rest in free space, as in the case of the cesium beam frequency standard, and when it is desirable to minimize the size of the device as in the rubidium frequency standard and the passive hydrogen maser.

Since all atomic frequency standards, both passive and active, derive their output signal from quartz oscillators, the performance of the atomic standards is significantly affected by the capabilities of those oscillators. In particular the very short-term frequency stability, the vibration sensitivity, the radiation sensitivity, and the sensitivity to thermal transients depend principally on the performance of the quartz local oscillator.

a. State Selection

Magnetic state selection and optical pumping are both used to manipulate the hyperfine state populations. Magnetic state selection is based on the concepts that have already been discussed. Examination again of Figure 11-1 shows that the energy of some of the Zeeman sublevels increase with increasing magnetic field; the energy of the remainder decrease. When the atoms are passed through a region of strongly varying magnetic field, they experience a force proportional to the rate of change of the field with distance. The

FIGURE 11-3. BLOCK DIAGRAM OF A GENERAL PASSIVE ATOMIC FREQUENCY STANDARD



atoms that increase in energy with increasing magnetic field are deflected towards the region of strong field; the atoms that decrease in energy with increasing magnetic field are deflected in the opposite direction. The method is illustrated schematically in Figure 11-4. Dipole, quadrupole, and hexapole optics are all used in atomic frequency standards to achieve the desired state population.

An alternate to magnetic state selection is optical pumping. This technique manipulates the populations in the hyperfine levels of the ground state by exciting transitions to higher principal quantum states with infrared, or higher, light. As shown in Figure 11-5, the atoms in one hyperfine level are excited optically to a higher state from which they decay spontaneously to both ground state hyperfine levels. The population of the hyperfine state involved in the stimulated transition is rapidly depleted; the population of the second hyperfine level is enhanced. Optical pumping has both advantages and disadvantages compared to magnetic state selection. On the positive side, it can be accomplished in a more compact device and it can enhance the number of atoms in the desired state rather than just rejecting the atoms in the undesired state. On the negative side are increases in complexity and some additional performance degrading mechanisms.

b. Detection of the Atomic Resonance

Passive atomic frequency standards use a variety of methods to detect the atomic resonance. That is, the standards detect the atomic transition probability as a function of the frequency of the applied radiation. The earliest approach was the direct detection of the state populations. The Stern-Gerlach experiment, which first demonstrated the quantization of angular momentum, used this method. A small background magnetic field established a reference direction. According to classical physics, the angular momentum of the silver atoms along this direction could take on any value between plus and minus to total angular momentum. A beam of silver atoms emitted from an oven passed through a dipole magnet and fell on a glass plate. The silver atoms were expected to deposit along a continuous line on the plate parallel to the magnetic field. However, only two spots were observed, demonstrating for the first time that the angular momentum along the field could have only two values. The amount of silver deposited indicated the populations of the two states.

An extension of this technique is still used. In a cesium beam frequency standard, upper state atoms may initially be selected using magnetic state selection. The application of microwaves near 9.2 GHz causes transitions to the lower state. A second magnet selects the lower state atoms, which subsequently fall on a hot ribbon in the detection region.

FIGURE 11-4. CONCEPT FOR THE MAGNETIC STATE SELECTION OF THE UPPER AND LOWER HYPERFINE STATES IN AN INHOMOGENEOUS MAGNETIC FIELD

Ball Efratom Division

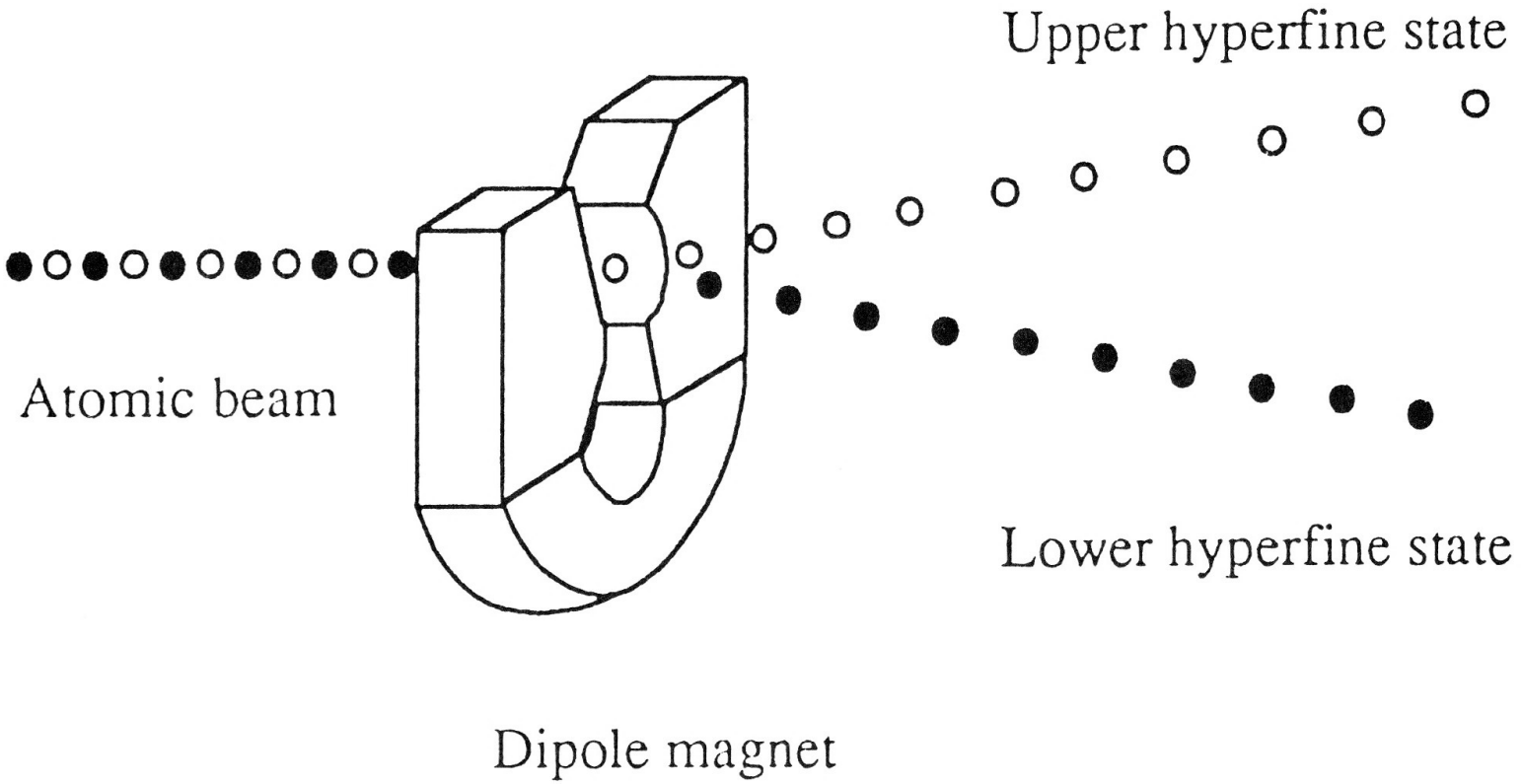
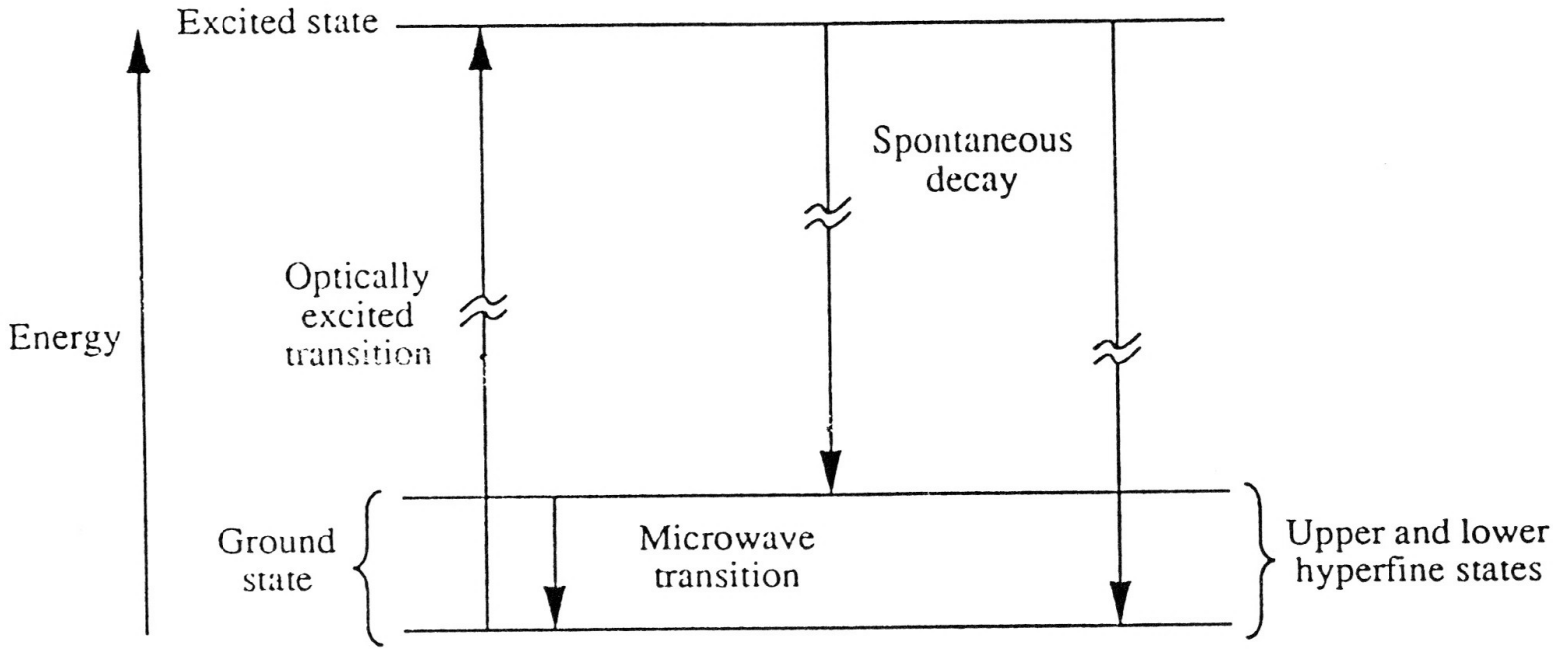


FIGURE 11-5. CONCEPT FOR OPTICAL PUMPING USING A THREE LEVEL SYSTEM



The cesium atom's ionization potential is significantly less than the work function for platinum or tungsten. Thus the cesium atoms give up an electron and are reevaporated from the wire as positive ions. Laboratory frequency standards collect the ions to indicate the number of atoms arriving at the detector. Commercial cesium beam frequency standards collect the cesium ions using a mass spectrometer to exclude impurities emitted from the ionizer. The cesium ion current is converted to an electron current by a specially treated surface on the first dynode of an electron multiplier. Since the conversion of cesium atoms to ions by the ionizer ribbon is near 100 percent, this method of detection provides nearly ideal preformance.

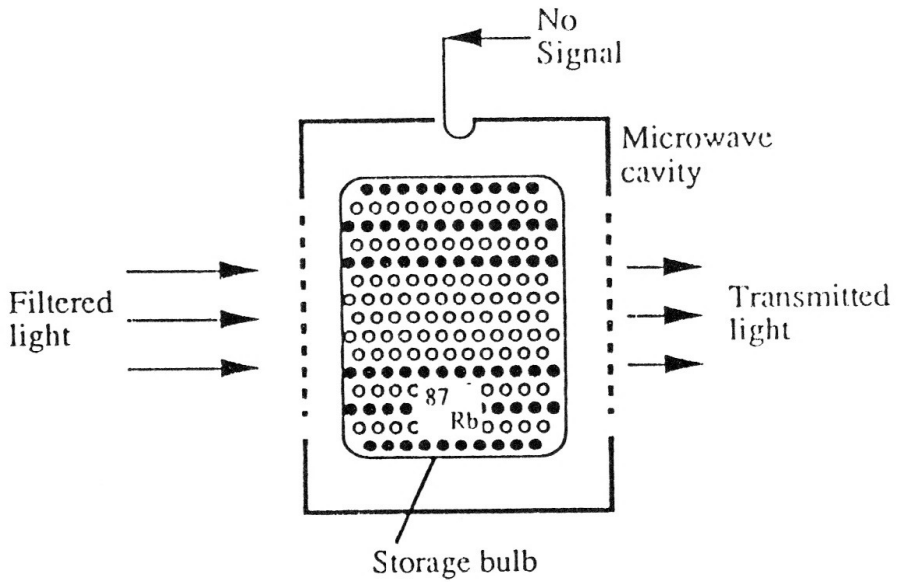
The effect of the microwave frequency on the transition probability can also be detected by its effect on the absorption of the light used to optically pump the atoms, such as in a Rb gas cell atomic frequency standard. With no microwaves applied, all the atoms are removed from one of the hyperfine states and the stored atoms become nearly transparent at the optical frequency. The transmission is maximum as depicted in Figure 11-6(a). Tuning the microwaves near the transition frequency causes atoms to be transferred back to the depleted level; the absorption then increases. Maximum absorption occurs at the peak of the transition probability as shown in Figure 11-6(b). The atomic resonance may also be detected by its effect on the microwaves themselves. The state selected atoms behave very much like a filter. If upper state atoms predominate, the microwave signal will experience amplification and phase shift. The microwave frequency which maximizes the transition probability may be determined by comparison of the signal passed through the atomic discriminator with a reference. This is the method used in a passive hydrogen maser frequency standard.

4. Systematic Limitations of Atomic Frequency Standards

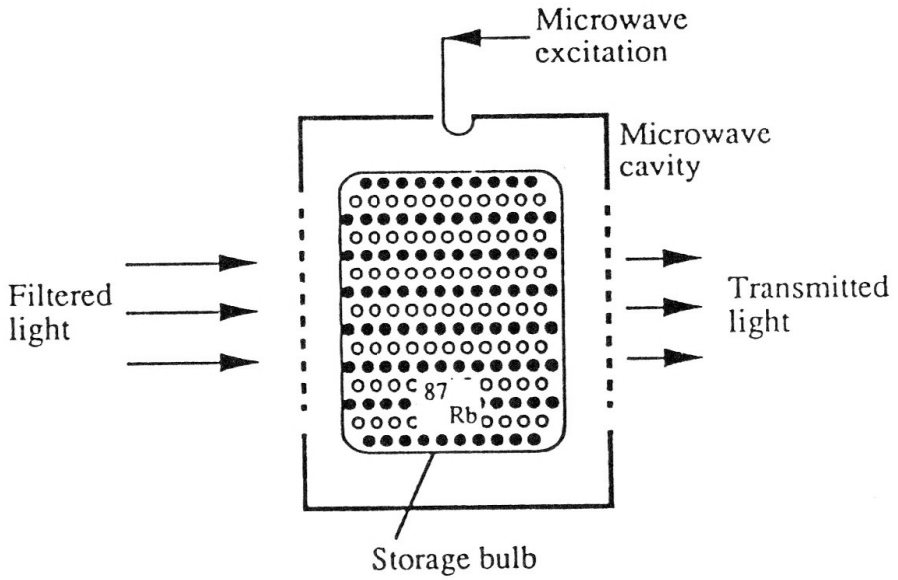
There are fundamental and practical limitations on the ability of a device to reproduce an atomic frequency. Quantum mechanics and thermal noise limit the quality of the measurements by producing stochastic frequency variations. Imperfections in the electronics, stray electric and magnetic fields, and interactions with other atoms cause the frequency standard to exhibit aging and temperature pressure sensitivities.

Atomic frequency standards must be designed to prevent performance limitation by the Doppler effect. The first order Doppler effect is the change in the observed frequency when a source is in motion relative to an observer. It is often observed as the change in pitch of a train whistle when the train overtakes and passes a stationary observer. Since

FIGURE 11-6. CONCEPT OF MICROWAVE RESONANCE DETECTION USING THE OPTICAL DENSITY OF THE ATOMIC MEDIUM



(a)



many atoms with different velocities must be observed in an atomic resonance as well as average frequency shifts. The observed Doppler frequency shift is equal to the ratio of the atomic velocity to the speed of light, approximately 1×10^{-6} for room temperature atoms, and would limit the maximum atomic Q to 1×10^{6}.

All atomic frequency standards use some form of first order Doppler shift cancellation in order to achieve Q's in the range of 10^{7} to 10^{9}. One method that is always used in microwave standards is to excite the atomic resonance with a standing wave produced by a microwave cavity. The atoms interact with microwaves of approximately equal intensity traveling in opposite directions and the Doppler shifts for these two interactions nearly cancel. Further cancellation is obtained when storage cells are used. The atoms in these devices change direction thousands of times while interacting with the microwave field. However, atom storage within a microwave resonator is insufficient to guarantee narrow, unshifted atomic lines. A more detailed analysis shows that the atoms must be confined to a region smaller than one-half wavelength. This restriction, known as the 'Dicke regime,' prevents frequency modulation due to the Doppler shifts from absorbing all the power from the carrier. Atomic beam frequency standards are always designed so that the residual power flow in the microwave cavity is orthogonal to the atomic beam direction. This construction takes the place of the velocity averaging of storage cell devices. Atomic beam standards must also operate under similar restrictions.

There are many other less fundamental perturbations to the observed atomic frequency. The atomic resonance is observed through the interaction of the atoms with the microwave field of a resonant circuit. If the cavity resonance frequency is not equal to the atomic frequency, the stronger fields at the cavity frequency increase the probablity of transitions at a frequency different from the true atomic frequency. In an active oscillator, the 'pulling' is equal to the error in the cavity resonance reduced by the ratio of the cavity Q to the atomic Q. In a passive atomic frequency standard, the pulling may be reduced by the square of the Q ratio.

In optically pumped frequency standards, the atomic energy levels are affected by the light used for the optical pumping. This problem is a specific instance of a phenomenon called the 'Stark effect,' which is the variation of atomic energy levels with applied electric fields. Other electric fields can usually be reduced to negligible levels, but the fields required for optical pumping are very intense and the resulting 'light shifts' are significant.

Frequency shifts are also caused by interactions of the atoms with other matter. These interactions change the hyperfine interaction energy. 'Pressure shifts' result from collisions with gas molecules. 'Spin exchange shifts' are caused by collisions of the subject atoms with each other. 'Wall shifts' result from collisions with the coating on a storage vessel. Additional changes in the measured maximum of the transition probability curve result from the presence of nearby atomic transitions. The tails of a neighboring transition result in a background slope, which distorts the measured shape of the desired transition.

Imperfections in the electronics cause additional errors in the measurement of the atomic transition frequency. Some of the problems are spurious microwave signals, voltage offsets and drifts, insufficient gain, and insufficient dynamic range. In the end, performance is always limited by the ability of the electronics to find the center of the atomic line, and a major thrust of research and development is toward achieving higher atomic line Q.

ATOMIC FREQUENCY STANDARD TYPES

1. Atomic Standards in Production

Three types of atomic standards are available to meet frequency stability requirements, which exceed the performance capabilities of quartz crystal oscillators: rubidium, cesium, and hydrogen frequency standards. Rubidium oscillators offer better stability in the range from one-hundred seconds to a few hours, a factor of ten improvement in long-term aging, superior reproducibility, and lower sensitivity to the environment. Rubidium frequency standards are often employed in tactical applications, or any time the clock must free run for a few hours to a day. Cesium standards offer further improvements. Compared to rubidium oscillators, they perform better for times longer than a few hours, generally suffer from no frequency aging, are more reproducible, and have lower sensitivity to the environment. Cesium standards are used in strategic applications and wherever a clock is required to keep time autonomously for much longer applications and wherever a clock is required to keep time autonomously for much longer than one day. The third type of standard, the active hydrogen maser, is used in applications requiring extreme coherence for periods of time from minutes to hours. Very long baseline interferometry and spacecraft tracking are the two principal applications.

Figure 11-7 is a schematic of a cesium beam tube. Spectroscopy is performed on cesium atoms in free flight through the microwave cavity in order to minimize environmental influences. A magnetic state selector prior to the cavity rejects atoms in the unwanted hyperfine level. A magnetic state selector following the cavity passes atoms having the state that was rejected in the first region. Thus, atoms must make a hyperfine transition in order to reach the hot wire ionizer. A feature of this beam tube, not previously discussed, is the U-shaped microwave cavity also called a Ramsey cavity. In this design, atoms are exposed to the microwave field, pass through a microwave field free region, and are then exposed to a second microwave field, in phase with the first. As a result, the atomic line is an interference pattern that maximizes the resolution of the spectrometer. Even more important, the design of the Ramsey cavity reduces the sensitivity to magnetic field inhomogeneities. Without it, the magnetic shielding requirement would be impractical.

Figure 11-8 shows a typical electronic schematic for the cesium frequency standard. A 5-MHz VCXO provides the output signal. After audio frequency modulation, it is used to synthesize the microwave signal at 9192.631 MHz, which is then used to excite the hyperfine transition. The detected atomic beam current from the beam tube is applied to a phase sensitive detector using the audio modulation as reference. After integration and additional loop filtering, the phase detector output is used to control the frequency of the 5-MHz VCXO. Figure 11-9 illustrates how phase sensitive detection generates a control signal that passes through zero at the resonance frequency.

Cesium technology has been optimized for long-term timekeeping and frequency reproducibility at the expense of size, weight, power, and warm-up time. A healthy device shows no frequency aging, and the reproducibility is on the order of 2×10^{-12} for the life of the cesium beam tube. The dominant long-term noise is random walk frequency, which limits the time keeping to approximately 0.1 microsecond per month.

The atomic spectrometer of a typical rubidium standard is shown in Figure 11-10. Commercial rubidium standards, based on the hyperfine transition in the ground state of Rb 87, are optically pumped using the light emitted from a Rb 87 discharge lamp. The emission from this lamp contains light with wavelengths corresponding to the transitions from the two hyperfine ground states to the excited state. The light from the Rb 87 passes through a region containing Rb 85. What makes rubidium standards practical is the fact that RB 85 strongly absorbs the wavelength that would excite the upper hyperfine state and transmits most of the lower state transition light. This filtered light is selectively absorbed by the lower hyperfine state atoms in the resonance cell. These atoms are

FIGURE 11-7. SCHEMATIC DRAWING OF A CESIUM BEAM TUBE

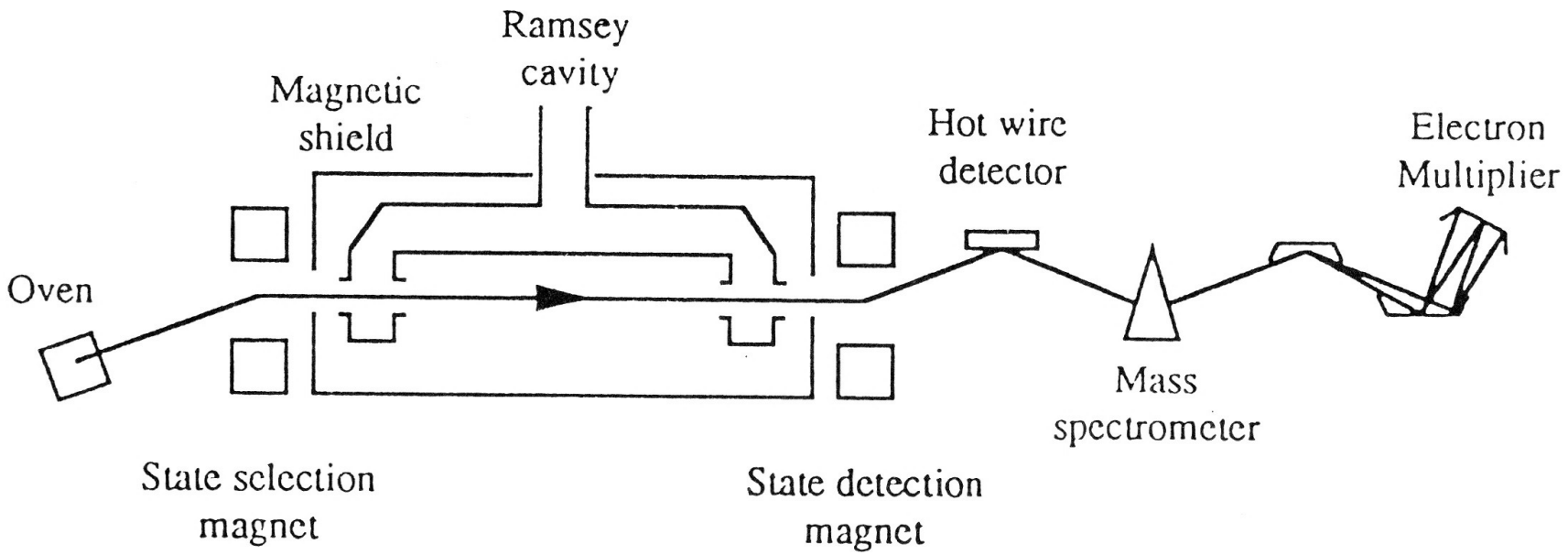


FIGURE 11-8. ELECTRONIC SCHEMATIC SHOWING THE FREQUENCY LOCK OF A VOLTAGE CONTROLLED QUARTZ OSCILLATOR (VCXO) TO AN ATOMIC (OR OTHER) RESONANCE

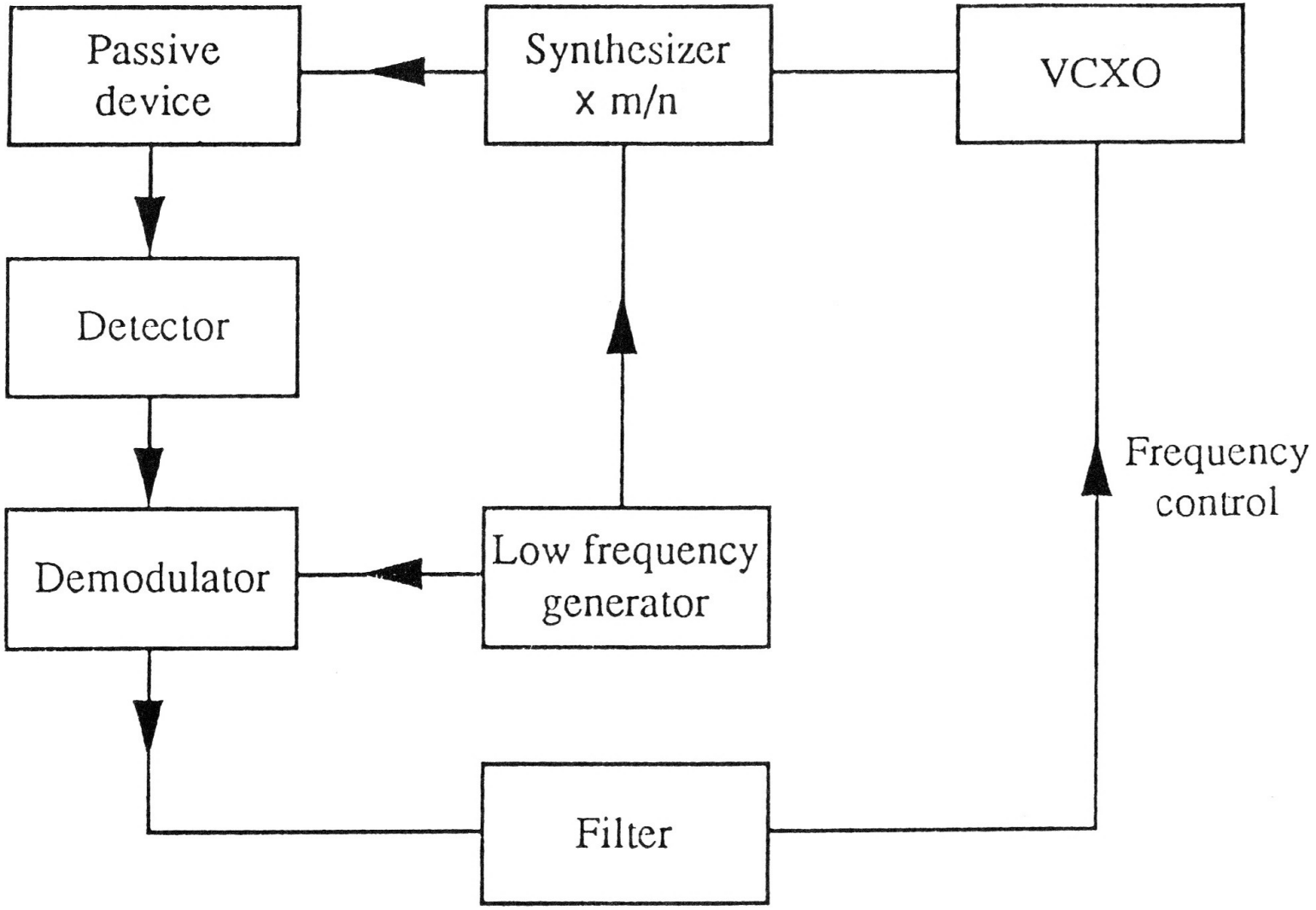


FIGURE 11-9. CONCEPT FOR THE DETECTION OF A PASSIVE RESONANCE USING SINUSOIDAL FREQUENCY MODULATION (FM).

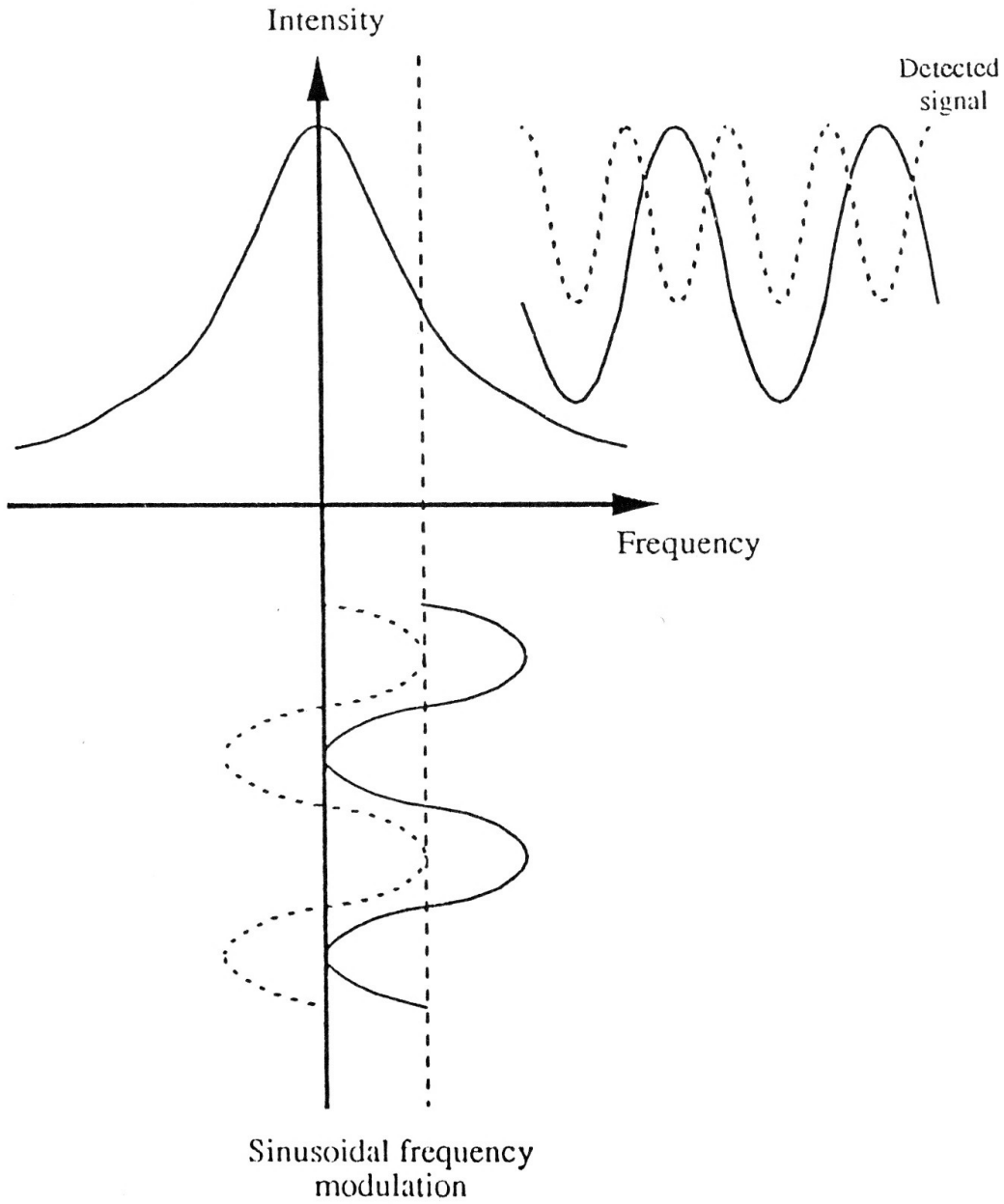
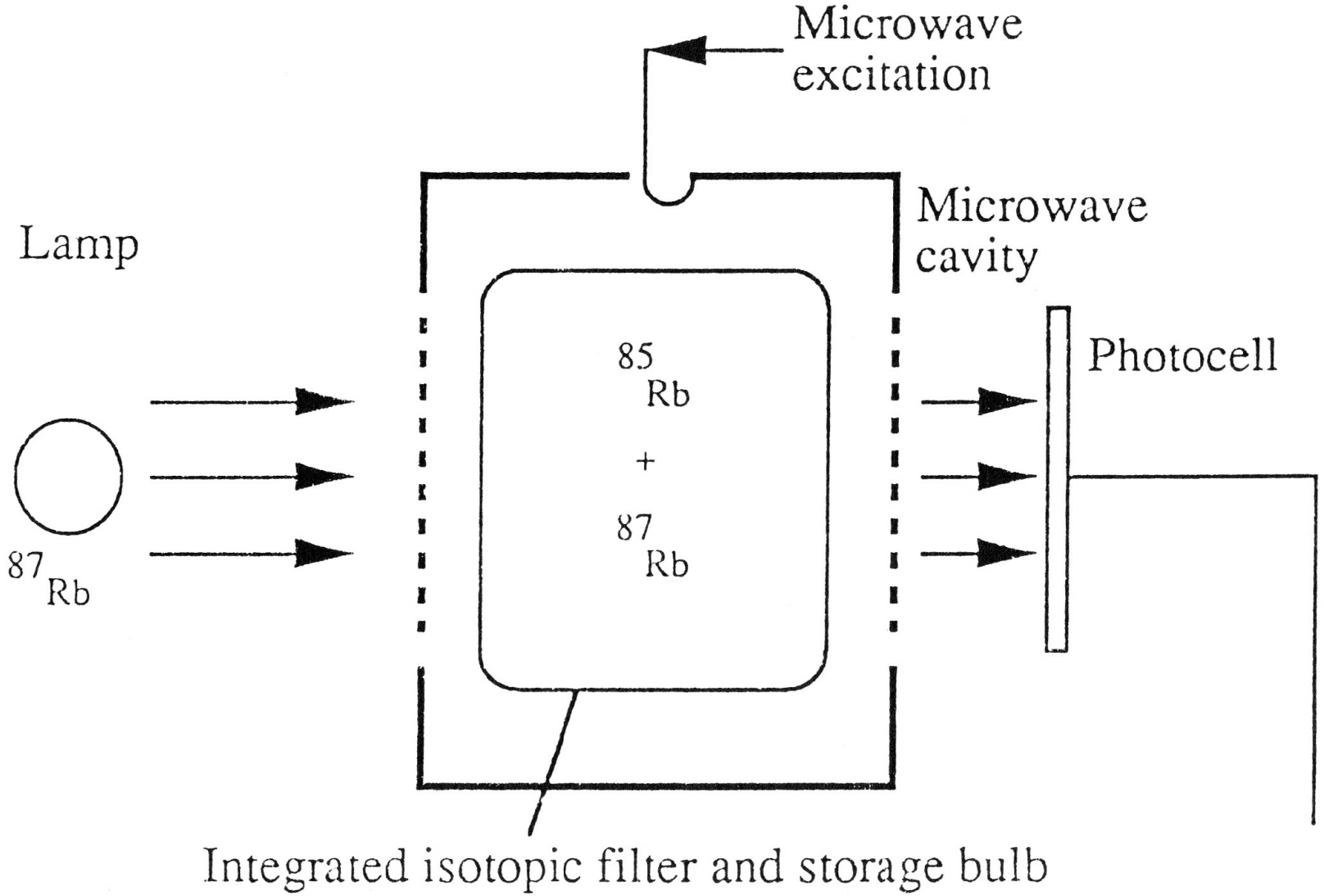


FIGURE 11-10. SCHEMATIC DRAWING OF THE ATOMIC SPECTROMETER FOR A PASSIVE RUBIDIUM FREQUENCY STANDARD

Ball Efratom Division



excited to a third, optical, state, which decays to both the ground state hyperfine levels. Atoms that return to the lower hyperfine level are excited again by the filtered light until they are converted into upper hyperfine level atoms.

Thus, the filtered light optically pumps Rb 87 atoms contained in the microwave resonance cell into the hyperfine state. In order to make a compact device, the resonance cell completely fills a small microwave cavity. The filter can be implemented separately, but most often is integrated with the cell by adding Rb 85. When microwaves are applied to the resonator cell, atoms are connected back from the upper to the lower hyperfine states. This increases the absorption of the filtered light that passes through the resonance cell. The Dicke criterion is satisfied within the resonance cell by using a buffer gas to localize the Rb 87 atoms during interaction with the microwave field. The buffer gas prevents the rubidium atoms from experiencing wall collisions that would introduce major perturbations. However, collisions of the Rb atoms with the buffer gas cause pressure shifts of the frequency. The resulting pressure and temperature coefficients can be set to zero at the normal operating temperature by using a mixture of gases, such as nitrogen and argon, that have opposite sign pressure shifts.

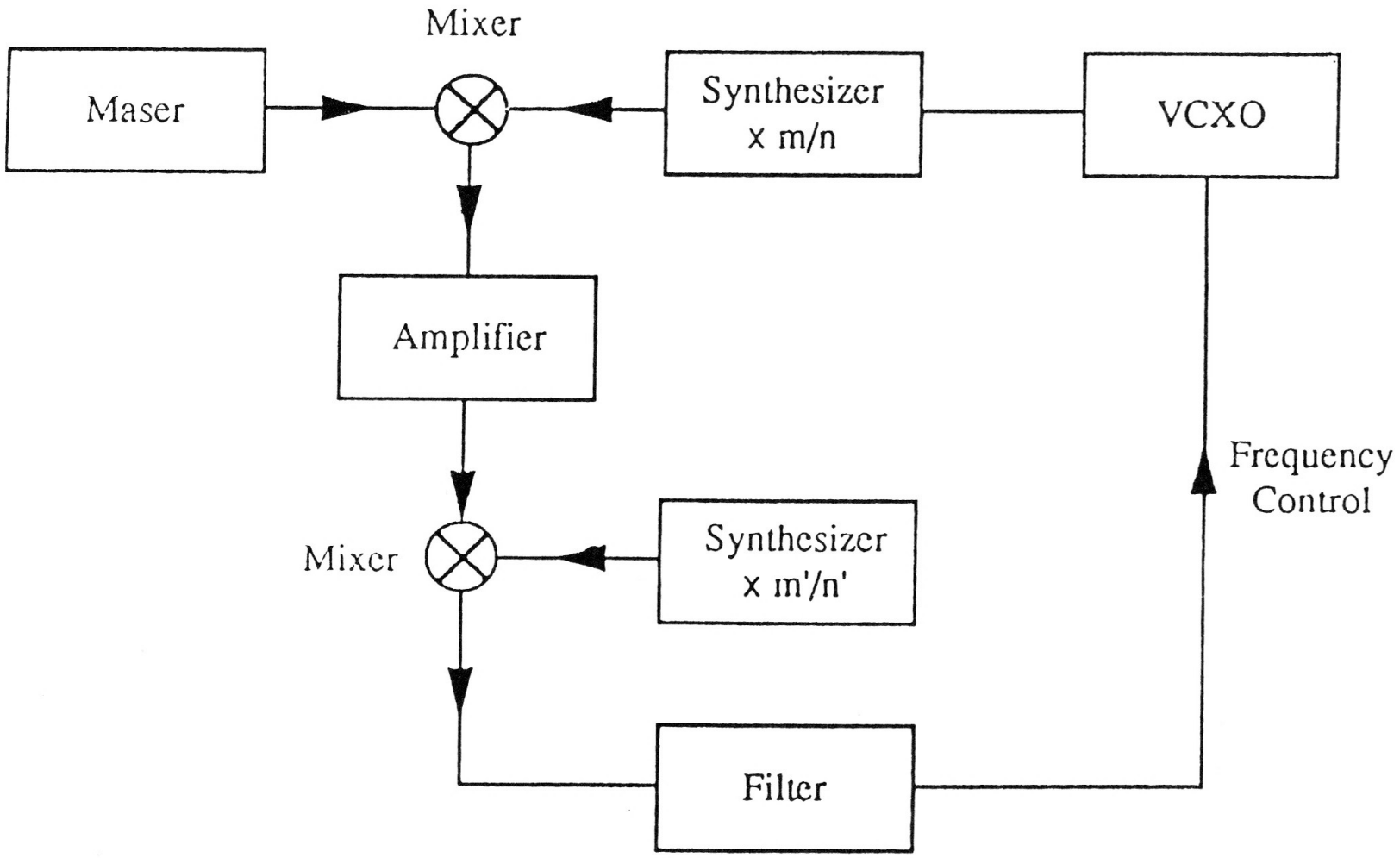
The rubidium standard control electronics is very similar to that of the cesium standard. The transition frequency is 6.834 GHz and the linewidth is several hundred Hz. The detection of the resonance is performed by a photodetector that measures the transmission of pumping light through the cell. There is approximately one to ten percent decrease in transmission when the microwave frequency is at the peak of the transition probability.

Rubidium technology has been optimized for small size and fast warm-up. The smallest is 5 cm by 7.5 cm by 10 cm, has a warm-up time of less than 4 minutes from 25°C for 1E-9 reproducibility, and the long-term frequency aging is 2×10^{-10} per year. Such a device does not have state-of-the-art frequency stability or phase noise. These performance parameters can be improved at the expense of increased size. In fact, a full-size rubidium standard, the same size as a cesium standard, performs almost as well as a cesium standard.

Figure 11-11 is a schematic representation of an active hydrogen maser. Unlike cesium and rubidium, hydrogen occurs only in molecular form at room temperature. The necessary atomic hydrogen is produced using a radio frequency discharge. Typically, the upper

FIGURE 11-11. SCHEMATIC DRAWING OF AN ACTIVE HYDROGEN MASER

Ball Efratom Division



state atoms are focused into a storage bulb using a hexapole state selector magnet. Eventually, spent atoms are pumped away. The bulb surface is Teflon coated to ensure nearly elastic collisions of the hydrogen atoms on the wall. This surface is so good that more than ten thousand bounces occur before the coherence of the hydrogen atoms is destroyed. Consequently, the observation time can exceed one second. As a result, the atomic line Q is greater than 1E-9, the highest of the commercial atomic frequency standards. The density of hydrogen in the storage bulb is limited by hydrogen-hydrogen collisions that alter the hyperfine energy and thus produce frequency shifts. A high Q microwave cavity is required to achieve self oscillation. The large size of most hydrogen masers (typical active hydrogen masers are ten times the volume of cesium frequency standards) results from the 1.4 GHz TE_{011} mode microwave cavity and the surrounding layers of magnetic shielding and temperature stabilizing ovens.

The control electronics for the active hydrogen maser is shown in Figure 11-12. The 1.42 GHz output from the atoms is amplified and mixed with a signal obtained by multiplying the output frequency to the microwave region. A final downconversion of this difference frequency using a reference synthesized from the output frequency completes the conversion of the atomic frequency to baseband. Feedback to the VCXO phaselocks it to the microwave signal originating from the atoms. In contrast to passive atomic frequency standards, which convert thermal noise at their preamplifier inputs to white frequency noise, the active maser converts this thermal noise to white phase noise. As a result, the short-term stability of active masers improves inversely with the measurement interval, as opposed to the stability of passive standards, which improves as the square-root of the measurement interval.

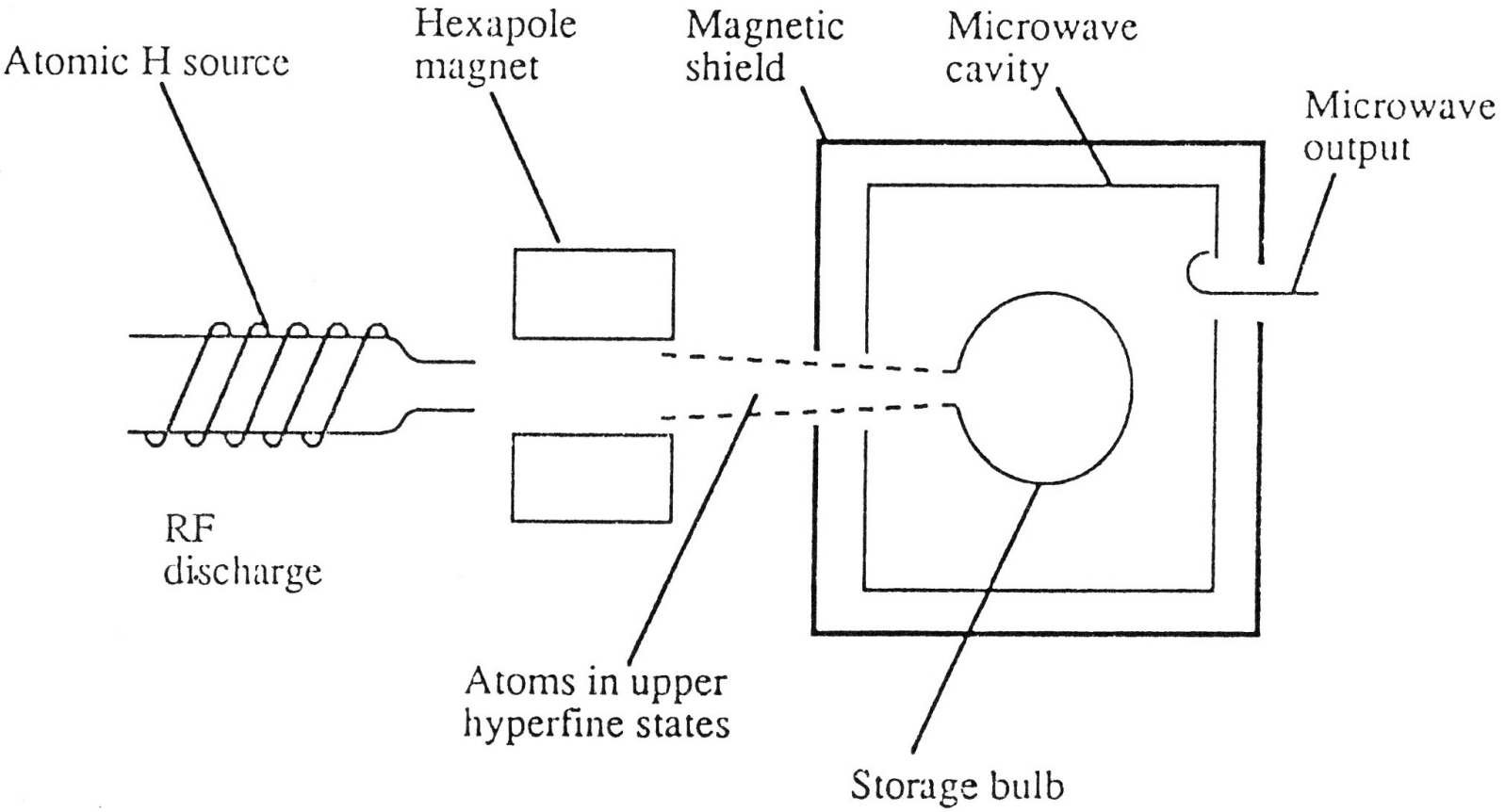
Active masers have the best short-term frequency stability of all the atomic frequency standards. Typical performance is 5E-13/τ, reaching a floor of better than 1E-15. However, the long-term performance is not as good as that of cesium frequency standards. Most masers have had substantial frequency aging that has been attributed to cavity pulling. The frequency stability at one day is typically 1E-14.

2. Experimental Atomic Frequency Standards

At the time of the writing of this section, in 1990, one of the most active areas of research in atomic frequency standards was atomic beam tube technology. The efforts are

FIGURE 11-12. ELECTRONIC SCHEMATIC SHOWING THE PHASE LOCK OF A VOLTAGE CONTROLLED QUARTZ OSCILLATOR (VCXO) TO THE ATOMIC RADIATION EMITTED BY AN ACTIVE MASER

Ball Efratom Division



directed towards two different and contradictory objectives, but both employ optical pumping technology. One goal is to develop a frequency standard with the low environmental sensitivity typical of the cesium standard, but having the size of a miniature rubidium standard. Optical pumping is used to replace the magnetic state selection and detection. Elimination of the high magnetic fields makes it possible to design a more compact device. The linear beam of an optically pumped device makes more efficient use of the atoms emitted from the oven than the usual magnetic optics, and helps achieve good short-term stability. The second goal is to improve the accuracy, reproducibility, and long-term stability of the atomic beam frequency standard. The performance limitations of the existing technology are due to residual first order Doppler shift, second order Doppler shift, and pulling by neighboring lines. The linear beam of the optically pumped device reduces the complicated coupling between the velocity and the position of the atoms in the beam, making it possible to better measure the Doppler effect. Optical pumping can also be used to transfer almost all the atoms to the desired hyperfine state, thus reducing the size of and pulling by neighboring magnetic field sensitive transitions. This technique can be combined with advances made in alignment of the beam tube to reduce the pulling problem to negligible levels.

The most promising developments for improving long-term stability of atomic frequency standards are in the field of ion storage. The goal of this work is to achieve the low interactions of the beam type frequency standard with the long observation times possible in a storage device. Singly ionized atoms, such as beryllium and mercury, have been stored using ion trap technology. The ions experience no collisions due to the storage mechanism, but are confined by the dc or rf electromagnetic fields. Mercury ion frequency standards have been built using the rf ion trapping technique. The technology appears practical for commercial application in the near term. Other ion frequency standard research uses Penning traps that employ dc trapping fields. This approach is compatible with laser cooling of the ions - a technique that extracts energy and momentum from the ions by scattering a laser beam. Cooling the ions below one Kelvin reduces the magnitude of the Doppler effects and improves the accuracy and reproducibility of the frequency standard. The large magnets and complicated lasers used for laser cooling will relegate this approach to the laboratory for some time to come.

GENERAL THEORY OF OPERATION OF EFRATOM Rb OSCILLATORS

The Efratom RFS generates a frequency-stable 10 MHz output signal from a voltage-controlled-crystal-oscillator (VCXO) which is locked to an atomic frequency reference. The atomic frequency reference is the 6.834 GHz ground state hyperfine transistion of ^{87}Rb (rubidium), as shown in Figure 11-13. The rubidium atoms that provide the atomic frequency reference are contained in a resonance cell within a resonator assembly. The VCXO is locked to the rubidium resonant frequency (f_{Rb}), at approximately 6.8 GHz, in the following manner. A microwave signal near f_{Rb} is synthesized from the 10 MHz VCXO output and used to excite the rubidium atoms contained within a microwave cavity. The frequency synthesis scheme is designed so that the VCXO frequency is exactly 10 MHz when the microwave frequency is exactly equal to f_{Rb}. The frequency of the signal applied to the microwave cavity can be maintained equal to f_{Rb} by generating an error signal when the microwave frequency differs from f_{Rb}. This error signal servos the VCXO through its control voltage, maintaining its frequency at exactly 10 MHz (within the capabilities of the control loop).

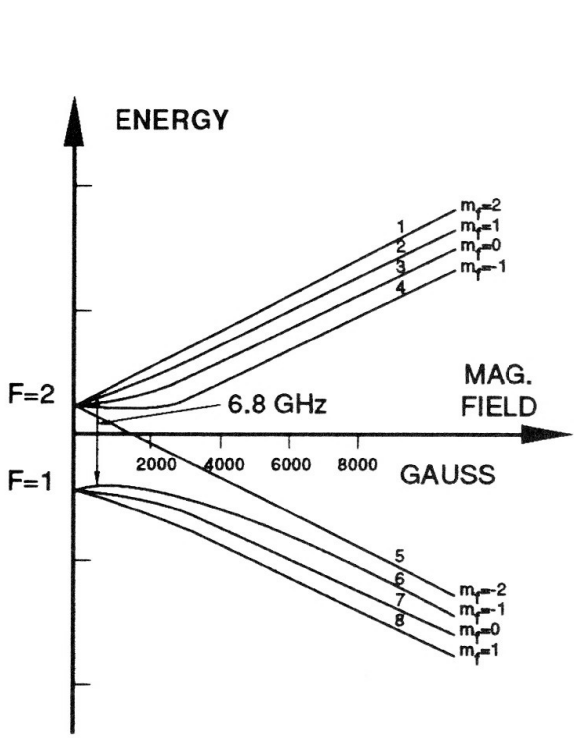
The error signal is generated by the physics package, which consists of the rubidium lamp and the resonator assembly. Light from the rubidium lamp is generated by an rf-excited plasma discharge and passes into the resonator assembly where it interacts with the rubidium atoms contained in the resonance cell. Some of this light reaches the photo-cell inside the resonator assembly. When the applied microwave frequency is equal to f_{RB}, the rubidium atoms resonate with the microwave field in the cavity. This causes the light reaching the photocell to decrease so that the photocell output current is a minimum at exact resonance (i.e., when the injected microwave frequency is exactly equal to f_{RB}). An explanation of this phenomenon requires a detailed description of the physics of rubidium atoms and their simultaneous interaction with light and microwave radiation. A microwave modulation technique is used to continuously minimize the photocell current, thereby locking the VCXO to f_{Rb}.

To enhance understanding of the operation of the rubidium standard, it is suggested that the reader refer frequently to the modulation concept (Figure 11-14), the simplified block diagram (Figure 11-15), and the detailed block diagram (Figure 11-16).

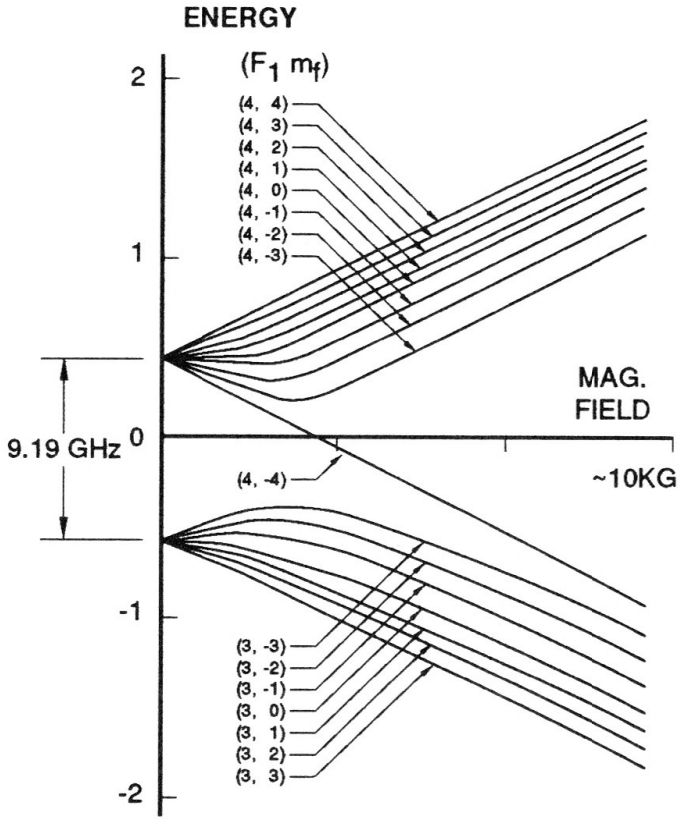
FIGURE 11-13. GROUND STATE HYPERFINE STRUCTURE

Efratom Division

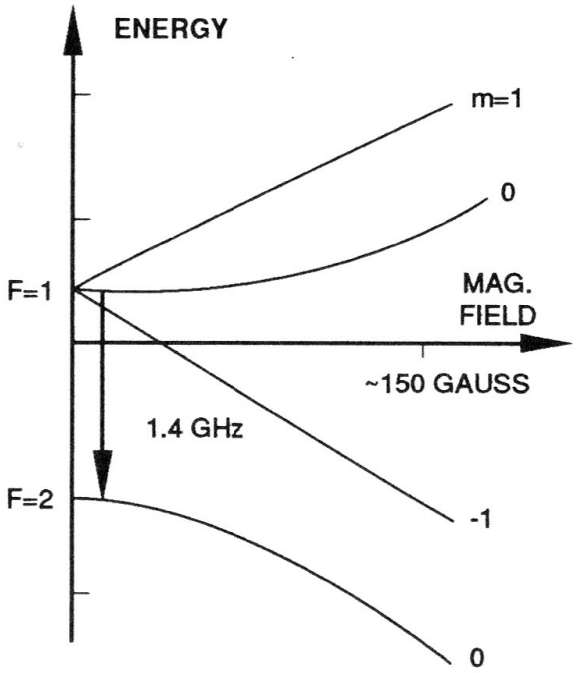
(ENERGY LEVEL DIAGRAM)



RUBIDIUM Rb^{87}



CESIUM Cs^{133}



HYDROGEN H^1

* DIAGRAM NOT DRAWN TO SCALE

FIGURE 11-14. MODULATION SIGNAL CONCEPT

Ball Efratom Division

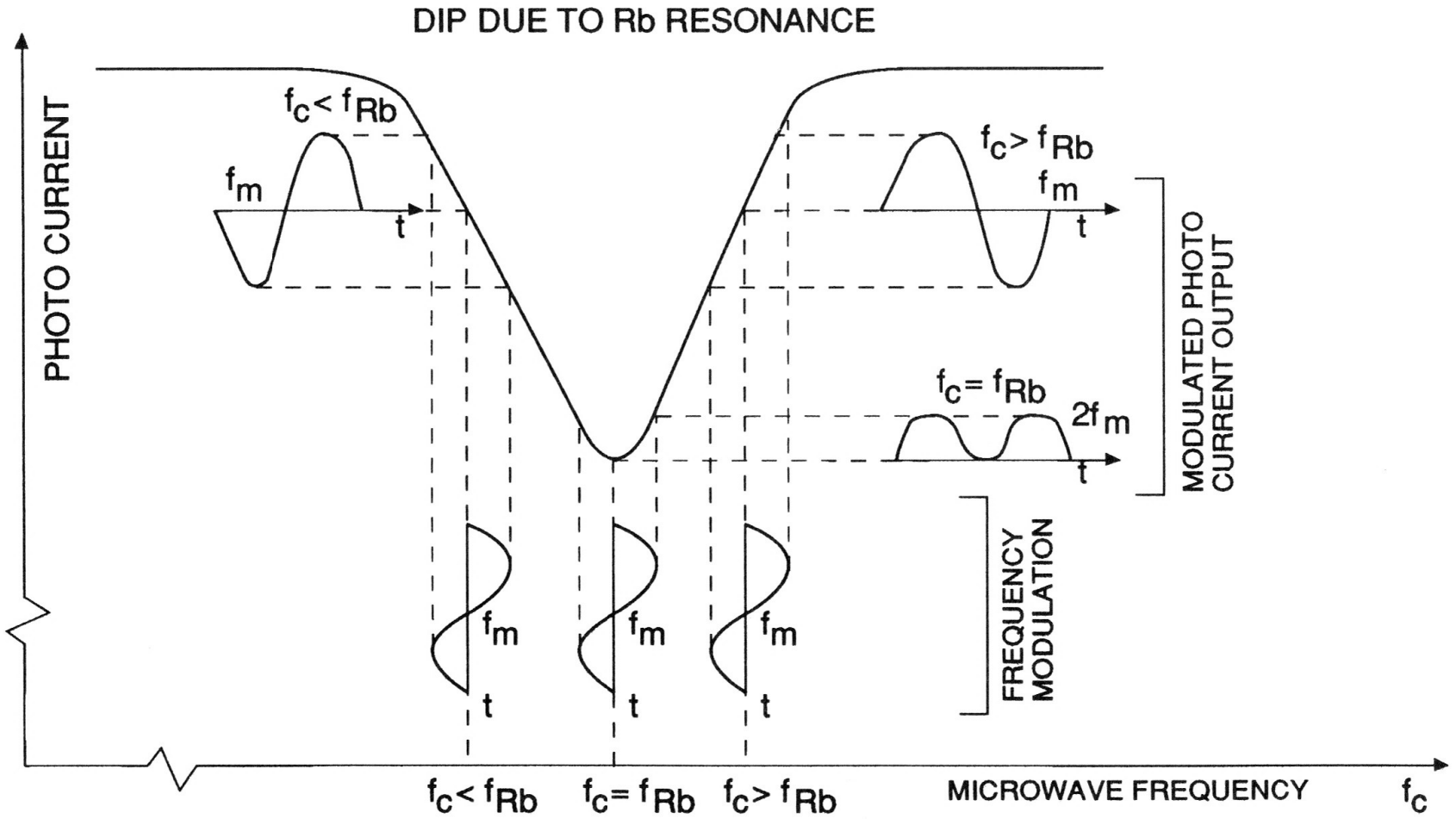
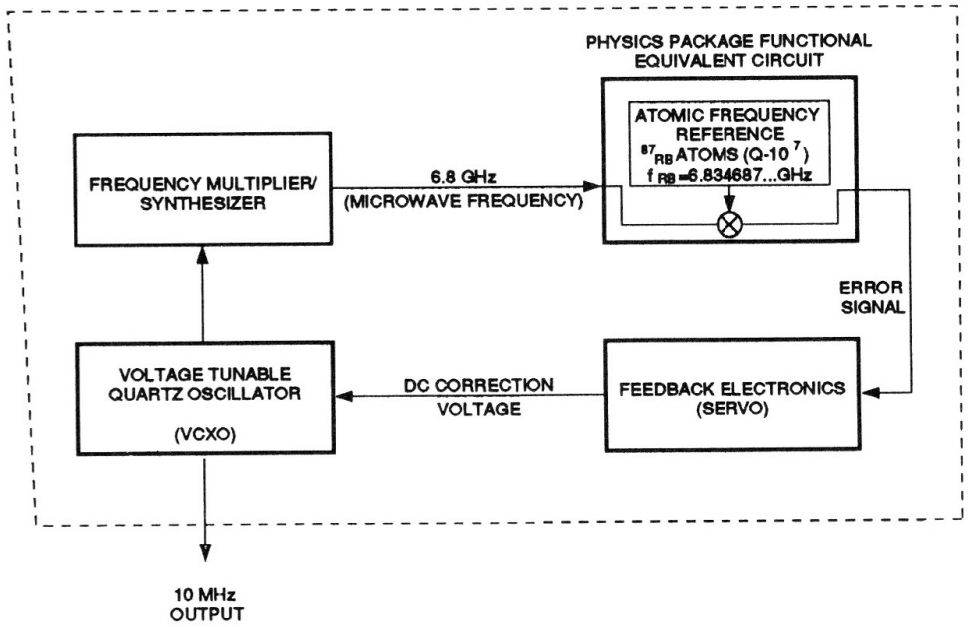


FIGURE 11-15. SIMPLIFIED BLOCK DIAGRAM AND PHYSICS PACKAGE



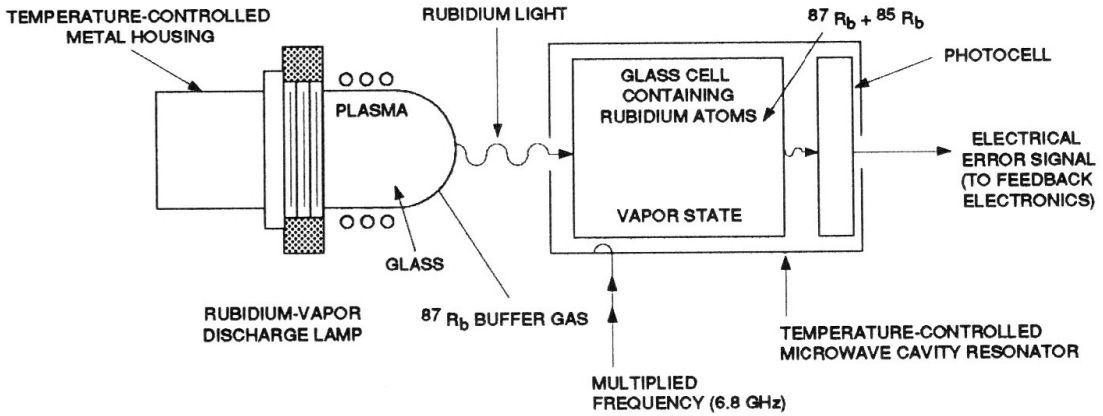
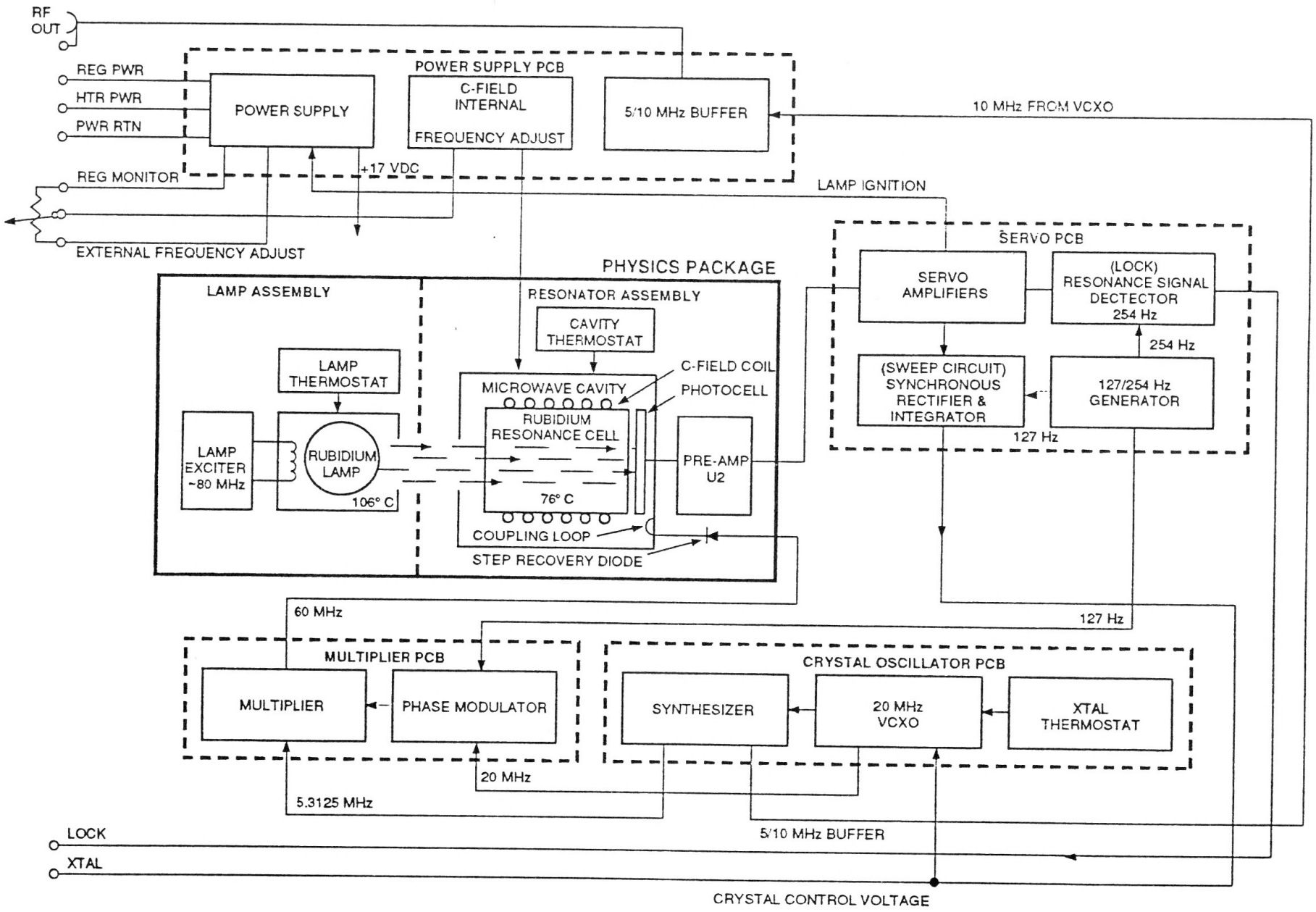


FIGURE 11-16. DETAILED BLOCK DIAGRAM

Ball Efratom Division



Atomic Reference Frequency/Physics package. The physics package consists of a resonator section and a lamp section, each supported by additional circuitry. It also contains the VCXO board, a photo preamp board, and a resonator heater board. The lamp section consists of a temperature controlled (thermostat'd) Rb lamp and an rf lamp exciter. The lamp exciter is sometimes referred to as the lamp oscillator. To maintain a sufficient and well-defined Rb vapor pressure in the lamp envelope, the lamp thermostat is set to approximately 115°C. A high-energy (~ 1 W) rf field of approximately 95 MHz is generated by the lamp exciter. This field starts and maintains an electrodeless plasma gas discharge in the lamp envelope. The lamp light contains the desired spectral lines of Rb necessary for the optical pumping process.

The resonator contains the integrated Rb cell, a photocell, a step recovery diode (with coupling loops), heater blankets and transistor, and the C-field windings. The density of the Rb atoms in the cell is thermostatically controlled in a manner similar to that used for the lamp.

A 60 MHz signal and a 5.3125 MHz signal are generated by the multiplier printed circuit board (PCB) and are fed to the step recovery diode/coupling loop mounted in the resonator cavity. This circuit generates radiation having frequencies given by the expression (60n + 5.3125m) MHz, where n = a positive integer and m = an integer. The microwave frequency (f) of interest here is that for which n = 114 and m = -1:

$$\begin{array}{r} 114 \times 60 \text{ MHz} \\ -\ 5.3125 \text{ MHz} \\ \hline 6\,834.687\,500 \text{ MHz} \end{array}$$

The Rb resonance cell and the multiplication/synthesis technique are utilized so that the microwave frequency is exactly equal to the ground-state hyperfine frequency of ^{87}Rb (f_{Rb} = 6834.687500 MHz) when the external output frequency of the RBO is exactly 10 MHz (corresponding to a VCXO frequency of exactly 10 MHz). Adjustment of the current flowing through the C-field coil allows fine tuning (parts in 10^9 and less) of the hyperfine transition frequency(through the second-order Zeeman effect) and therefore the 10 MHz output frequency.

With the correct microwave signal generated in the cavity and the proper Rb vapor pressure in the lamp and cell, the light intensity passed by the cell will be a function of the microwave frequency. Figure 11-14 illustrates this concept. The photocell output current is proportional to the intensity of the light incident upon the photocell. When the injected microwave frequency f is exactly equal to the frequency f_{Rb} of the ground-state hyperfine transition of ^{87}Rb, maximum energy is absorbed from the pumping light resulting in minimum photo current.

The "dip" in the photo-current-versus-microwave-frequency curve of Figure 11-14 is very small: on the order of 0.1% of the total photocurrent. For this reason, dc detection of the dip is not feasible and an ac detection method is utilized. The ac method involves phase modulating (or frequency modulating, depending on the relative phasing) the microwave radiation at an audio frequency f_m (~254 Hz). As shown in Figure 11-14, this modulation produces a corresponding modulation of the output current from the photocell. When the microwave frequency is exactly equal to the rubidium hyperfine frequency ($f = f_{Rb}$), the modulated photo current contains no ac component at the modulation frequency f_m, but there is a component at twice the modulation frequency $2f_m$ (~512 Hz). The presence of this second harmonic of the modulation indicates that the VCXO is locked to the hyperfine transition. If the microwave frequency is greater than the rubidium frequency ($f > f_{Rb}$), then the photo current will contain an ac component at the fundamental frequency f_m that is in phase with the original modulation at frequency f_m. If the microwave frequency is lower than the rubidium frequency ($f < f_{Rb}$), then the photo current will contain an ac component at the fundamental frequency f_m that is 180° out of phase with the orginal modulation at frequency f_m.

The dc error signal that is used to correct the frequency of the VCXO is derived from the ac component of photo current at the fundamental frequency f_m by synchronous rectification (demodulation) of the latter. As can now be understood from the previous description, when the VCXO is exactly on frequency (10 MHz) there is no ac component of photo current at the fundamental frequency f_m of the modulation and therefore no corresponding dc error signal (in this case, there is no need to correct the VCXO frequency). Should the VCXO frequency drift upwards, the microwave frequency will also drift up and the condition $f > f_{Rb}$ will occur. Synchronous rectification of the ac component of the photo current will, in this case, produce a positive dc error signal that is proportional to the amplitude of the fundamental component. Conversely, if the VCXO frequency drifts down instead of up, the condition $f < f_{Rb}$ will occur. In this case, the synchronous rectification will produce a negative dc error signal that is proportional to the amplitude of the fundamental component of the photo current. The sign reversal is due to the 180° phase change in the modulated photo current when $f < f_{Rb}$. The phase information contained in the fundamental component of the photo current is used to steer the VCXO frequency and cancel the offset, therefore locking it to f_{Rb}.

The modulation scheme described above is implemented by phase modulating (at f_m) the 60 MHz signal on the multiplier PCB which, when multiplied by 114 by the step recovery diode, produces frequency modulation (at f_m) of the 6.8 GHz microwave signal. The resulting ac photo current is amplified on the preamp board and synchronously rectified on the servo PCB to provide the dc error signal. However, instead of routing the dc error signal directly to the VCXO, it is electronically integrated and then routed to the VCXO. This then completes the description of the servo loop. This type of servo loop is commonly used in passive atomic frequency standards and is known as a "frequency-locked loop."

Electronic Analogue of Physics Package. The physics package is a passive device in the sense that the ^{87}Rb atoms must be "interrogated" by externally-generated microwave radiation; the atoms themselves do not produce a self-sustaining oscillation at the atomic hyperfine frequency. To a first approximation, the behavior of the ^{87}Rb atoms in the resonance cell can be represented by an electrical analogue, as shown in Figure 11-17. In this analogue, the atoms behave like an ultra-stable, high Q ($Q \sim 10^7$), series-resonant RLC tank circuit that is resonant at the hyperfine frequency ($f_{Rb} = 6.834 \ldots$ GHz). The analogue of the microwave signal derived from the 10 MHz VCXO is a frequency-modulated voltage source operating at f = 6.8 GHz to drive the tank circuit. Similarly, the analogue of the photocell is a square-law current detector and a low-pass filter.

Optical Pumping. In the actual physics package, the atomic resonance is detected by optical means, specifically by a decrease in the intensity of the Rb light transmitted by the resonance cell when the frequency (f) of the interrogating microwave signal is in the vicinity of the atomic resonant frequency ($f \sim f_{Rb}$). To understand why this effect occurs, it is necessary to consider the atomic physics phenomenon known as "optical pumping". In this section an oversimplified description of the optical pumping process is given that serves to illustrate the basic principle involved in the detection of the atomic resonance. In all that follows, it is important to note that the frequency f_o of *any* atomic resonance transition is related to the difference in the energies E_o of the two atomic energy levels, between which the transition occurs, by the fundamental equation of physics,

$$F_o \text{ (Hz)} = E_o \text{ (joules)}/h,$$

Where h = Planck's constant = 6.6262×10^{-34} joules/Hz.

FIGURE 11-17. ELECTRICAL ANALOGUE OF PHYSICS PACKAGE

Ball Efratom Division

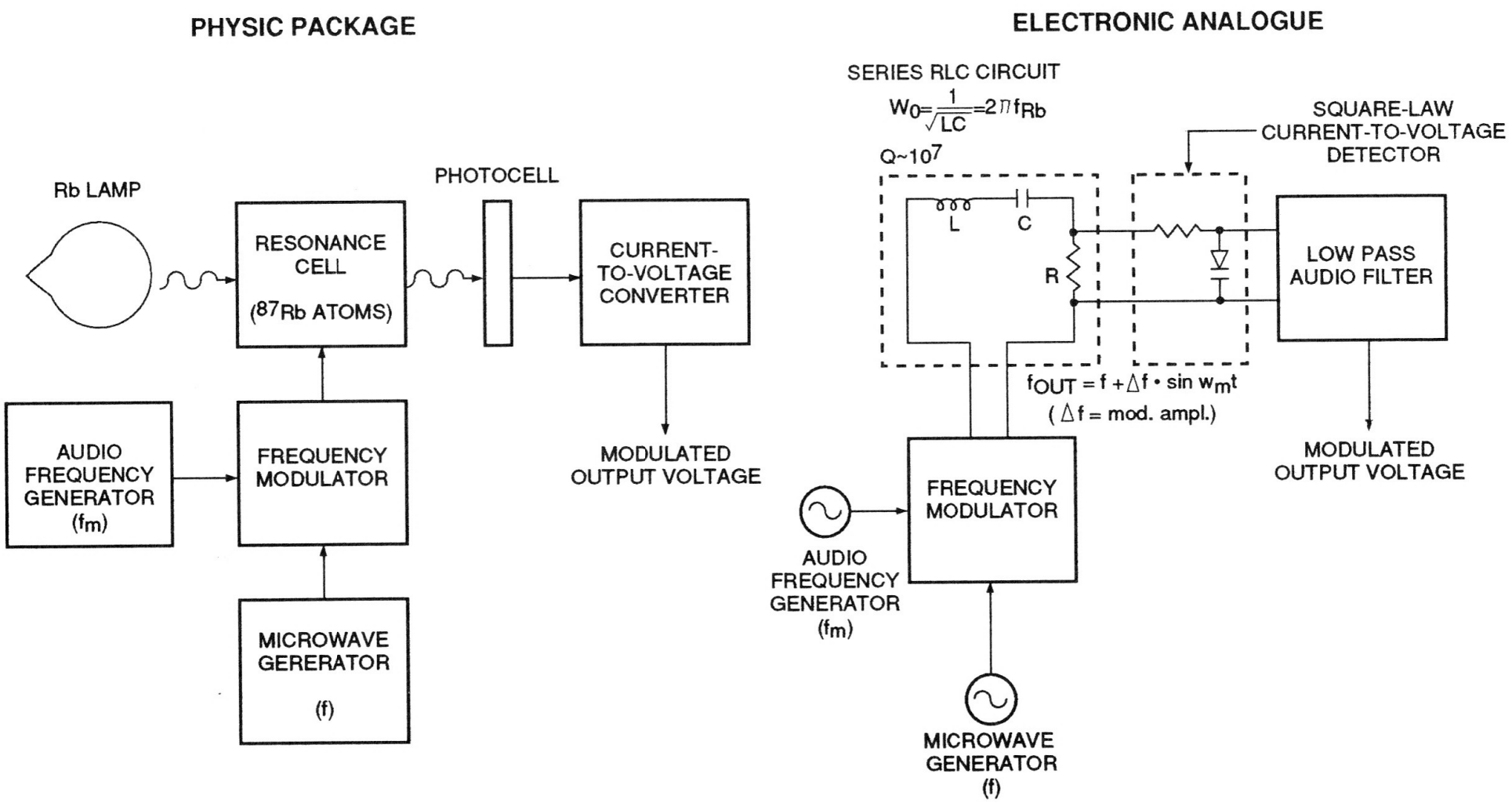
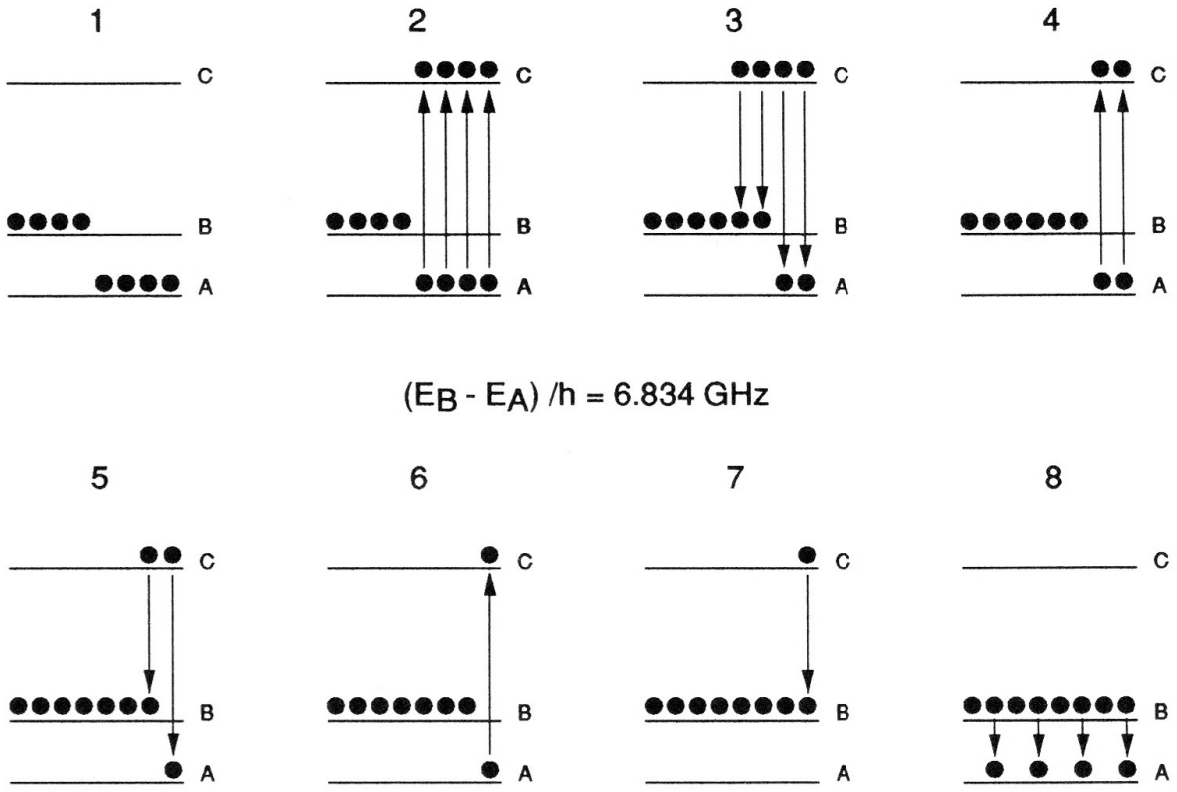


Figure 11-18 is a simplified diagram of the energy levels involved in the optical pumping process. The two lower levels, A and B, are the two ground-state hyperfine levels. In the absence of light from the rubidium lamp, the rubidium atoms in the resonance cell will be equally divided between these two levels, as indicated in frame 1 of Figure 11-18. If the atoms are irradiated with microwave energy at the hyperfine frequency, then those atoms in level A will make a transition to level B and vice-versa, without changing the number of atoms in each of the two levels (both levels still equally populated), and the transitions will not be detectable. However, if a method can be found to create a difference in the atom populations of the two states A and B, then the transition can be detected (as is described below). The method used to create a population difference is called "optical pumping" and in the case of the RFS it is used to transfer (or "pump") atoms from level A to level B. As the name implies, the pumping is done indirectly by optical means and involves a third energy level of atoms labelled C in Figure 11-18. (For the ^{87}Rb atom, the energy spacing between level C and level A is approximately 55,000 times greater than the spacing between levels B and A, therefore, the diagram is not to scale.)

Level C is an optically-excited state of the atom that is normally vacant. For rubidium, the C level state is excited by infrared light energy of the proper wavelength from the rubidium lamp. Transitions to level C are known as "optical transitions" and can occur from either of the two hyperfine energy levels A or B. If only the spectral wavelength corresponding to *one* of the hyperfine levels is introduced (no microwave radiation is present), only the atoms in that hyperfine level will make the transition to level C. This condition can be realized by removing the spectral wavelength corresponding to the hyperfine level B using the method of optical hyperfine filtering.

FIGURE 11-18. OPTICAL PUMPING PROCESS ILLUSTRATED



If the light energy injected into the resonance cell corresponds to the wavelength required for level A to C transitions, the rubidium atoms at the A level will absorb some of the light. As indicated in frame 2 of Figure 11-18, this absorption of light raises those atoms to the higher C level energy state. After a short time (~ 30 ns) the atoms that were raised to the C level will emit a photon of approximately the same wavelength as that which raised the atoms to the optically-excited state; they then return to the ground-state hyperfine level, redistributing themselves approximately equally between levels A and B (frame 3). The atoms which return to level A will again absorb the light and be raised to level C, where they will again remain for a short time before emitting photons and again redistributing themselves between the two hyperfine energy levels A and B (frame 4). By this optical pumping method, a population difference is produced between the two hyperfine levels whereby all of the atoms are pumped from level A into level B (frames 5-7). Once this idealized condition exists, there are no atoms left in level A to be excited to level C and the light is not the proper wavelength to excite the atoms in level B to level C (frame 7). Therefore, no light attenuation occurs when the light passes through the resonance cell.

When a microwave field corresponding to the hyperfine frequency is now applied simultaneously with the pumping light, the atoms in level B make transitions to level A and are then available for excitation to level C by the light beam. Since each optical excitation of an atom from level A to level C requires the absorption of a light photon, the net effect of applying the microwave field is to cause attentuation of the light beam with the attenuation being greatest when the frequency, f, of the microwave field is exactly equal to the hyperfine frequency, $f_{Rb} = (E_B - E_A)/h$. This explains the origin of the "dip" in Figure 11-14. Modulation Signal Concept.

The Zeeman Effect. The Zeeman effect, named after its discover Pieter Zeeman, the Nobel prize winning Dutch physicist, is the phenomenon of the splitting of a single spectral line (or energy level) of an atom into several components when the atom is placed in a static (non time varying) magnetic field.

Figure 11-19a shows the low-lying energy levels of the ^{87}Rb atom. The 5 S state is the ground state and the two 5 P states are the first optically-excited states. The separation of the two 5 P states is known as "fine-structure splitting". (For clarity of illustration, the separation of the 5 P states is exaggerated relative to the 5 S - 5 P separation.) If the ground 5 S state is examined using a 20,000 power magnifying glass, it will be found that the 5 S state is composed of two energy levels, the ground-state hyperfine levels, which are shown in the "inset", and are labelled F=2 and F=1. The separation of these two levels is known as "hyperfine splitting". If a static magnetic field is applied to the ^{87}Rb atom, these two hyperfine levels split into distinct sublevels, each having a different energy that depends on the strength of the magnetic field. This magnetic splitting is referred to as the "Zeeman effect", and the individual sublevels as "Zeeman levels". The various separations and their fundamental physical causes are listed in Table 11-1 using one consistent set of units (electron volts, or eV).

FIGURE 11-19.THE ZEEMAN EFFECT

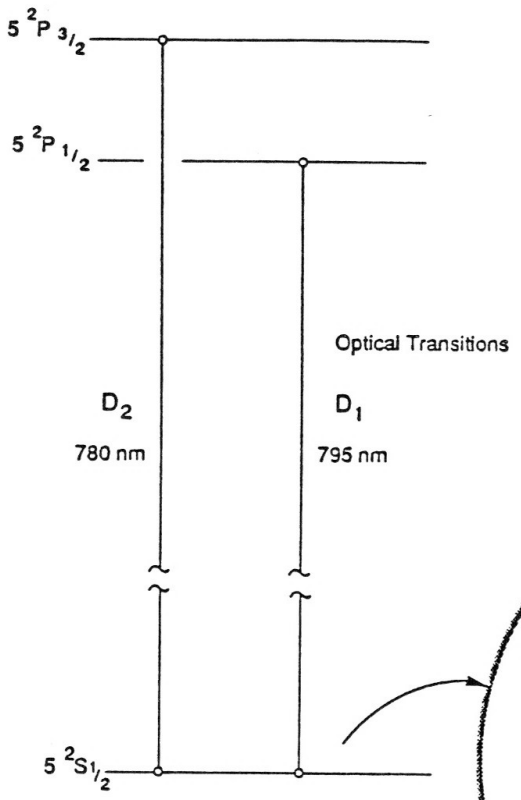


Figure 11-19a Low- Lying Energy levels of ^{87}Rb

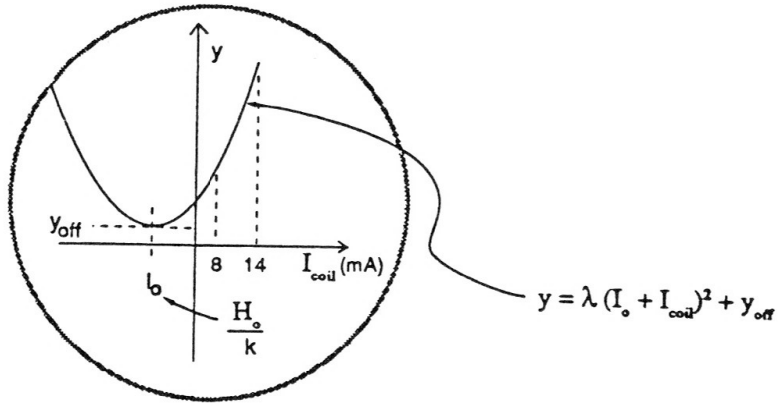


Figure 11-19b Frequency vs C-field Coil Current Relationship for the clock transition.

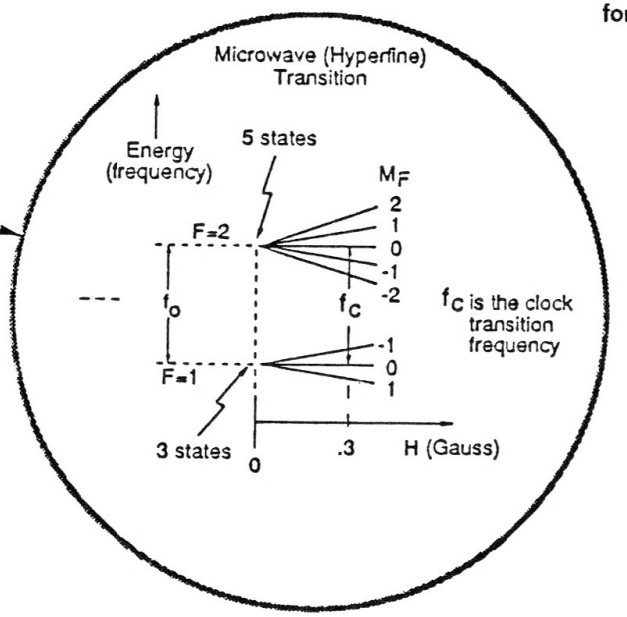


Table 11-1. ^{87}Rb Energy Level Separations

Separation	Name	Mechanism	Energy(eV)
5 S - 5 P	Optical	Coulomb interaction of outer electron with inner atomic core.	1.6
5 P - 5 P	Fine Structure	Spin-orbit interaction of outer electron (relativistic interaction).	0.03
5 S: F=2 - F=1	Hyperfine Structure	Interaction of the magnetic dipoles of the outer electron & the atomic nucleus with each other.	3E-5
Within an F state	Zeeman Splitting	Interaction of the magnetic dipoles of of the outer electron & the atomic nucleus with an external magnetic field.	<<1E-5

The optical transitions, D1 @ 780 nm and D2 @ 795 nm, give rise to the so-called "resonance lines" of ^{87}Rb. These very intense lines are used for optical pumping and signal detection in the rubidium frequency standard.

The Zeeman levels, as can be seen from the inset in Figure 11-19b, are designated by the quantum number M_F. (To adequately specify a Zeeman level the values of both F and M_F must be given.) Generally speaking, the dependence of the energies of these levels upon magnetic field H can be expressed as a rapidly convergent power series in H having the form,

$$E(F, M_F) = E_0(F) + A1*H + A2*H^2 + A3*H^3 + A4*H^4 + \ldots$$

It can be shown from elementary quantum mechanics that the coefficient A1 has the form

$$A1 = K*M_F$$

where K = -0.70 MHz/Gauss for the F=2 level of ^{87}Rb, and K = +0.70 MHz/Gauss for the F=1 level of ^{87}Rb.

It follows from the above expression that the energies of those Zeeman levels for which M_F is different from zero have a very strong linear dependence on magnetic field, whereas the energies of the $M_F = 0$ levels have no linear dependence, and are therefore field independent to the first order. At low fields (below several tens of Gauss) the levels therefore behave as shown in the inset of Figure 11-19a, and the Rb standard (or clock) transition is chosen to be the transition between the $(F,M_F) = (2,0)$ and (1,0) levels. This choice for the clock transition makes the clock transition frequency relatively insensitive to the presence of external magnetic fields. Specifically, it can be shown that magnetic field dependence of the clock transition frequency f_c is given by

$$f_c = f_o + 575*H^2$$

where H has units of Gauss, the frequencies are in Hz, and f_o is the clock transition frequency when no magnetic field is present. Thus an external field of 1 Gauss will produce shifts of at least 0.70 MHz in the field dependent transitions ($M_F = 0$), but only 575 Hz for the clock transition, (recall that A1 = 0 since $M_F = 0$).

The practical implementation of the Zeeman effect is to fine tune the rubidium frequency by means of the current flowing through a coil ("C-field") wrapped around the resonance cell. The magnetic field strength H is related to the coil current according to

$$H = H_o + k * I_{coil}$$

where H_o, which is the residual field at the cell without any coil current, can be either positive or negative, and k is a constant depending on the coil geometry. Since the clock transition provides a quadratic relationship between F_c and H, the resulting relationship of frequency vs coil current is

$$f_c = f_o + 575\, k^2 (I_o + I_{coil})^2$$

where

$I_o = H_o/k$ (I_o can also be positive or negative).

Since the fractional frequency offset $y = \dfrac{(f_c - f_o)}{f_o}$,

then $y = 8.41 \times 10^{-8}\, k^2 (I_o + I_{coil})^2$. In reality, a frequency offset term y_{off} (on the order of ±1E-10) exists accounting for imperfections in the control loop; the result is $y = \lambda (I_o + I_{coil})^2 + y_{off}$, where λ is nominally 5E-11. This relationship is shown in Figure 11-19b. $\dfrac{}{mA^2}$

The pressures and gas mixtures of the cell are selected initially to require a positive frequency offset of roughly 4E-9 to 10E-9 from the C-field coil to be at the desired output frequency. Even though the correction of the coil is not linear (the slope is a linear function of the required coil current), the desired frequency settability is obtained over the range of coil currents required by using a quality multi-turn potentiometer for fine frequency adjustments, selected for the desired resolution at the anticipated maximum coil current.

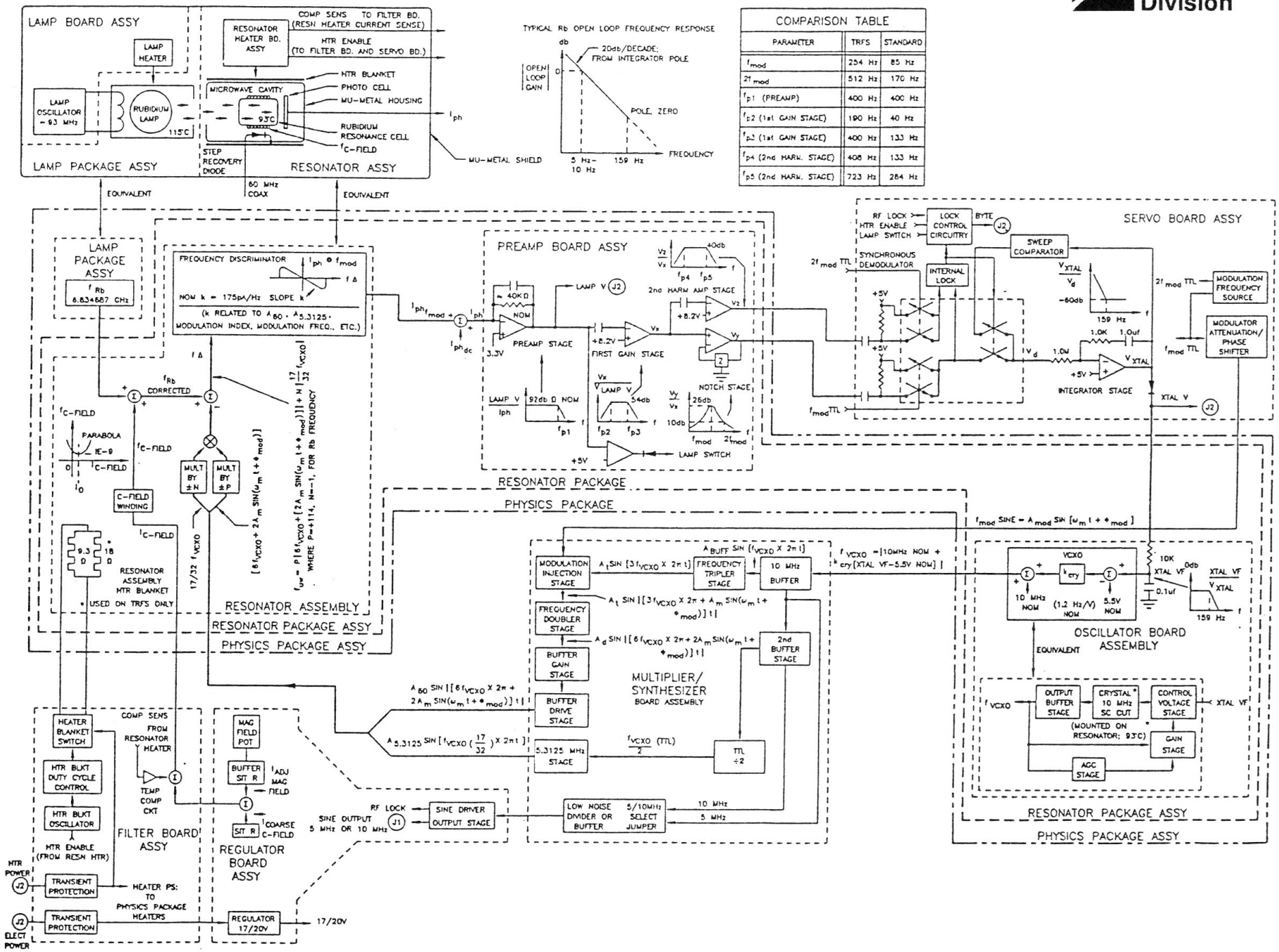
The block diagram shown in Figure 11-20 functionally illustrates the physics package and associated circuitry that encompass the operation of the RFS rubidium frequency standard.

The primary blocks shown are the physics package assembly, along with the servo board assembly, the multiplexer/synthesizer board assembly, the regulator board assembly, and the filter board assembly. The physics package assembly has sub-blocks of the lamp package assembly and the resonator package assembly (which in turn is composed of the resonator assembly, preamp board assembly, oscillator board assembly, and resonator board assembly).

The summing mode is shown in the resonator assembly, as the difference between the rubidium frequency (corrected by the effects from the C-field current) and the microwave frequency. The error signal detected by the photocell is presented to the preamp, suitably bandpass amplified, demodulated and integrated. The resulting integrator output (V_{XTAL}) is filtered, then presented to the VCXO. The oscillator output frequency is boosted to a microwave signal by means of the multiplexer synthesizer, along with the snap diode located in the resonator microwave cavity; this closes the loop.

FIGURE 11-20. RUBIDIUM OSCILLATOR BLOCK DIAGRAM

Ball Efratom Division



THE BASIC PRECISION OSCILLATORS

- Quartz
- Rubidium
- Cesium
- H-Maser

HIGH PERFORMANCE OSCILLATORS

The most popular and available precision oscillators today fall into four categories:

(A) High-Performance Quartz Crystal Oscillator
(B) Rubidium Gas Cell Atomic Oscillator
(C) Cesium Beam Atomic Oscillator
(D) Hydrogen Maser Atomic Oscillator; Active and Passive

As one can see from this list, three of these categories deal with devices that utilize atomic physics principles; the Quartz Crystal Oscillator category does not.

Quartz Crystal Oscillators

The precision oscillator industry has generally adopted standard output frequencies of 5 MHz and 10 MHz. These frequencies are eminently suitable for fabrication of the quartz crystals that are used in the manufacture of stable, low-noise quartz oscillators, such as the one shown in the next figure. The oscillating element is obviously the quartz disc when stimulated by an electric field. In order to obtain very high daily stability, the effects of temperature and other environmental factors on the crystal must be reduced by complex quartz cutting, mounting, and fabrication methods, as well as sophisticated electronic control circuits in the oscillator.

CRYSTAL OSCILLATOR CATEGORIES

The three categories, based on the method of dealing with the crystal unit's frequency vs. temperature characteristic, are:

· **XO, crystal oscillator,** which does not contain means for reducing the crystal's f vs. T characteristic (also called PXO- packaged crystal oscillator).

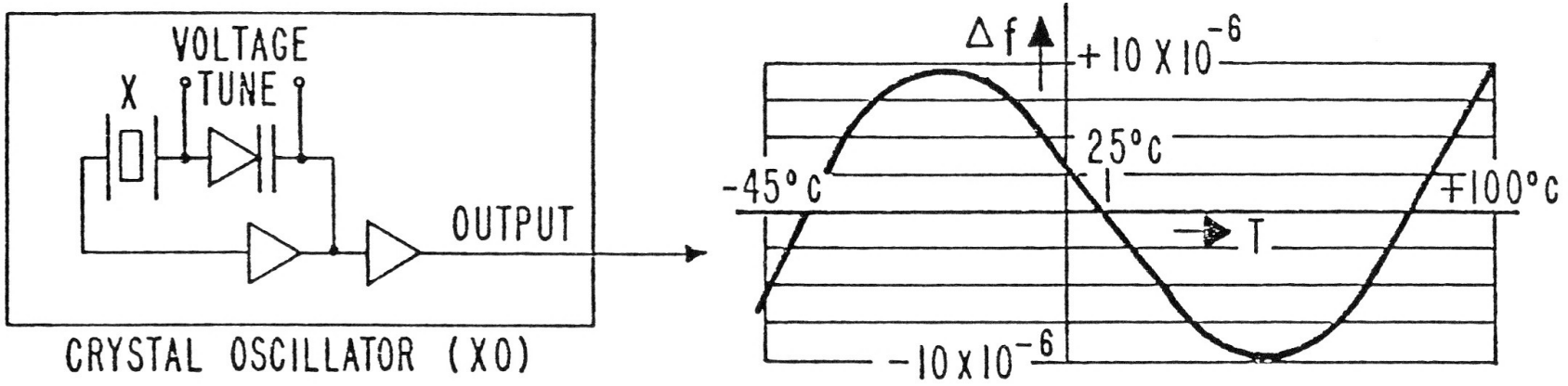
· **TCXO, temperature compensated crystal oscillator,** in which the output signal from a temperature sensor (thermistor) is used to generate a correction voltage that is applied to a voltage-variable reactance (varactor) in the crystal network. The reactance variations compensate for the crystal's f vs. T characteristic. Analog TCXO's can provide about a 20X improvement over the crystal's f vs. T variation.

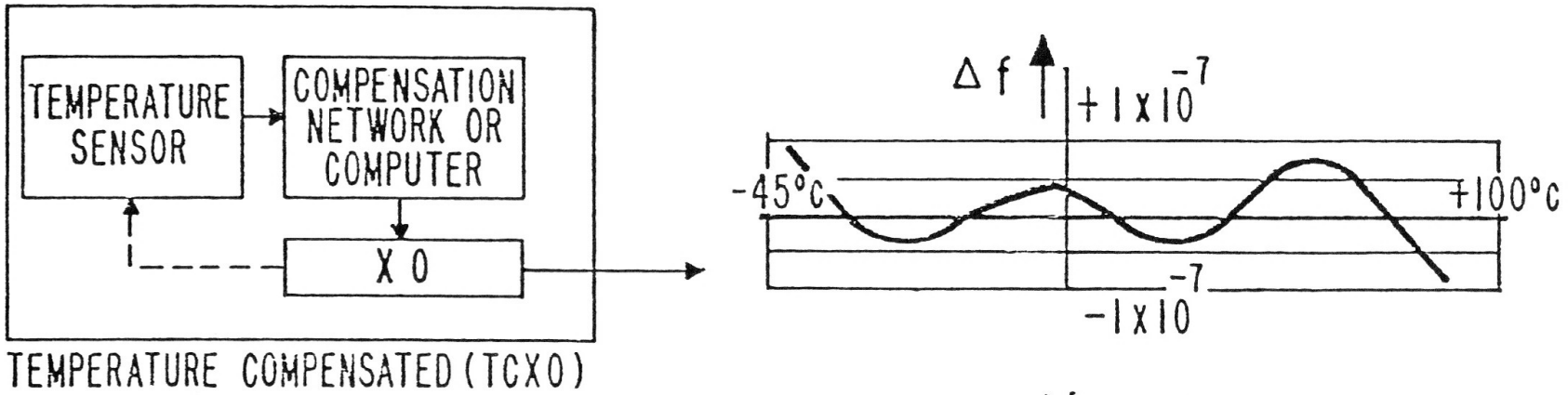
· **OCXO, oven controlled crystal oscillator,** in which the crystal and other temperature sensitive components are in a stable oven which is adjusted to the temperature where the crystal's f vs. T has zero slope. OCXO's can provide a >1000X improvement over the crystal's f vs T variation.

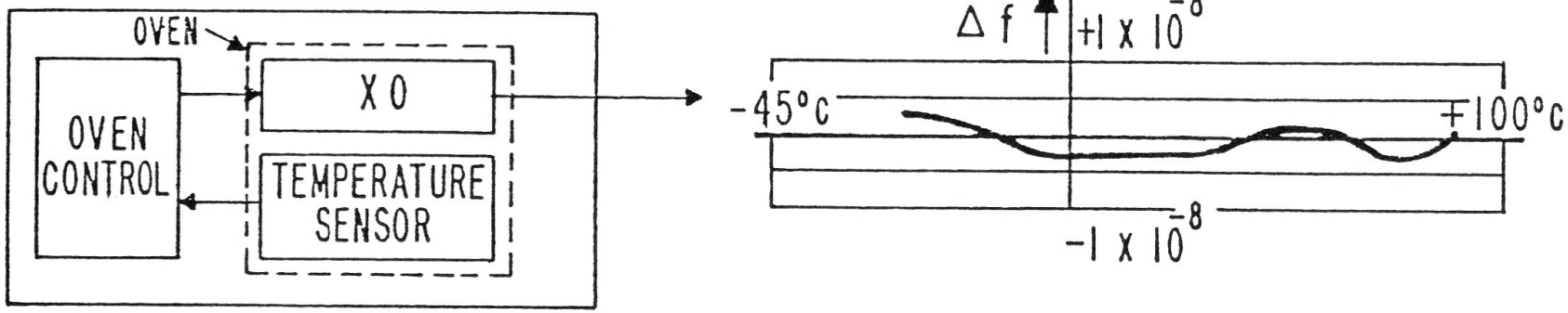
Courtesy of John Vig, Army-LABCOM

MAIN CATEGORIES OF QUARTZ CRYSTAL OSCILLATORS

Ball Efratom Division







Courtesy of John Vig, Army-LACOM

THE PRECISION QUARTZ OSCILLATOR

ADVANTAGES	DISADVANTAGES
• LOWER POWER CONSUMPTION	• AGING
• SMALL SIZE AND WEIGHT	• RETRACE
• HIGH MTBF	• TEMPERATURE COEFFICIENT
• HIGH TEMP. OPERATION	• RADIATION SENSITIVITY
	• ACCELERATION SENSITIVITY

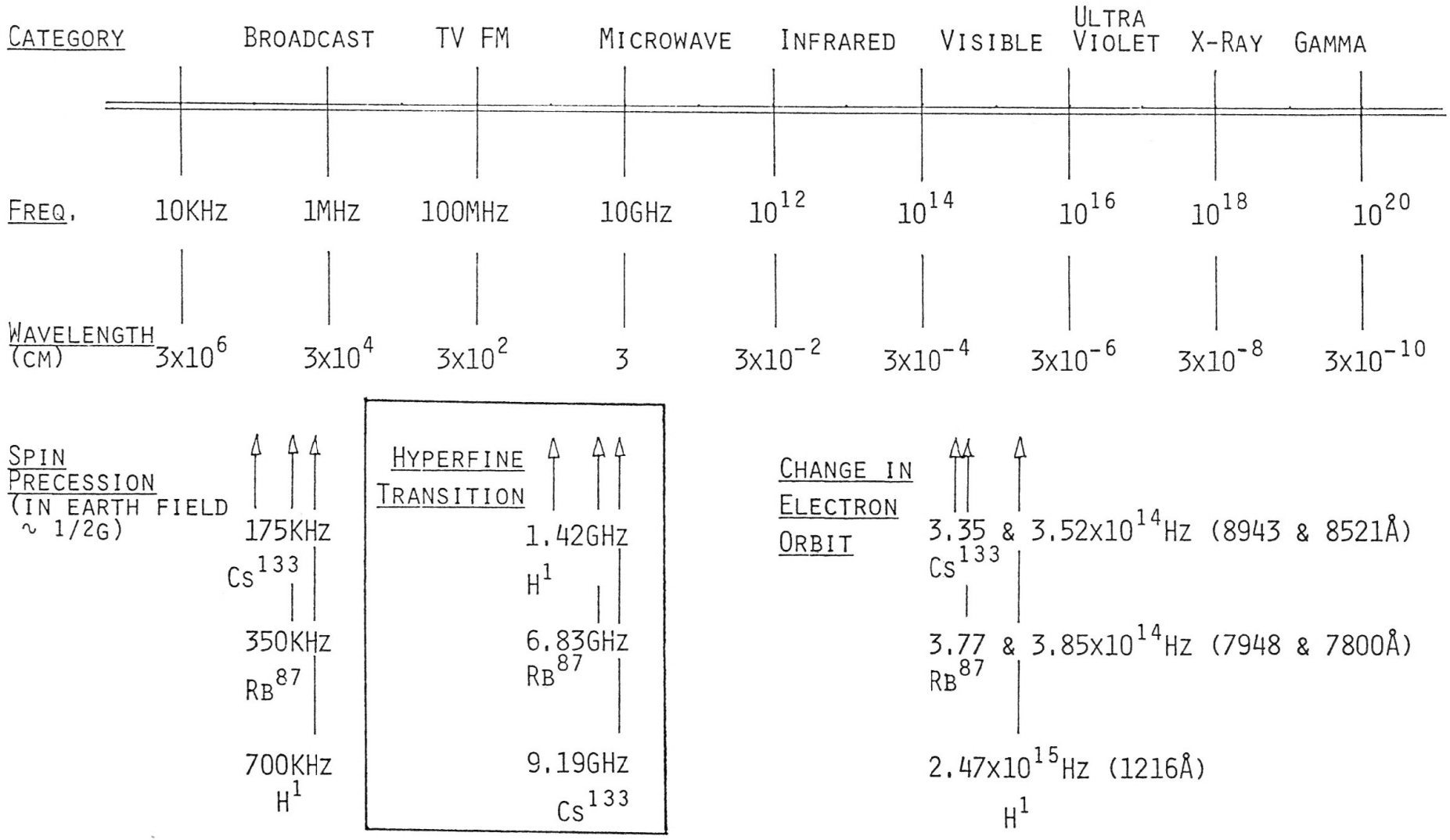
Depending on the type of crystal-cut used, the super-quartz OCXO oscillator can be quite large (about 3 x 3 x 4 in; 7.6 x 7.6 x 10.2 cm) compared to the less sophisticated performer, (about 1.5 x 1.5 x 2 in). For the SC-cut crystal, thermal control and insulating requirements are generally reduced and usually allow for smaller packaging. The Efratom EMXO/ECXO Series may be the smallest, high performance OCXO available (about 1.3 x 1.3 x 1.3 in).

THE ATOMIC OSCILLATORS

Each of the three oscillators in the atomic class utilizes a different atom, but the basic principle is the same for each. A voltage-controlled crystal oscillator (VCXO) is locked to a highly stable frequency reference generated by a microwave transition in the atom of interest. The stability and environmental insensitivity of this atomic reference frequency are thereby transferred to the VCXO. The atomic transitions of interest are referred to in the vernacular of physics as ground-state hyperfine transitions. Although atoms can absorb and emit electromagnetic energy at many different frequencies, the hyperfine transitions are selected because they are highly stable, relatively insensitive to environmental effects, and occur in a reasonable convenient region of the spectrum.

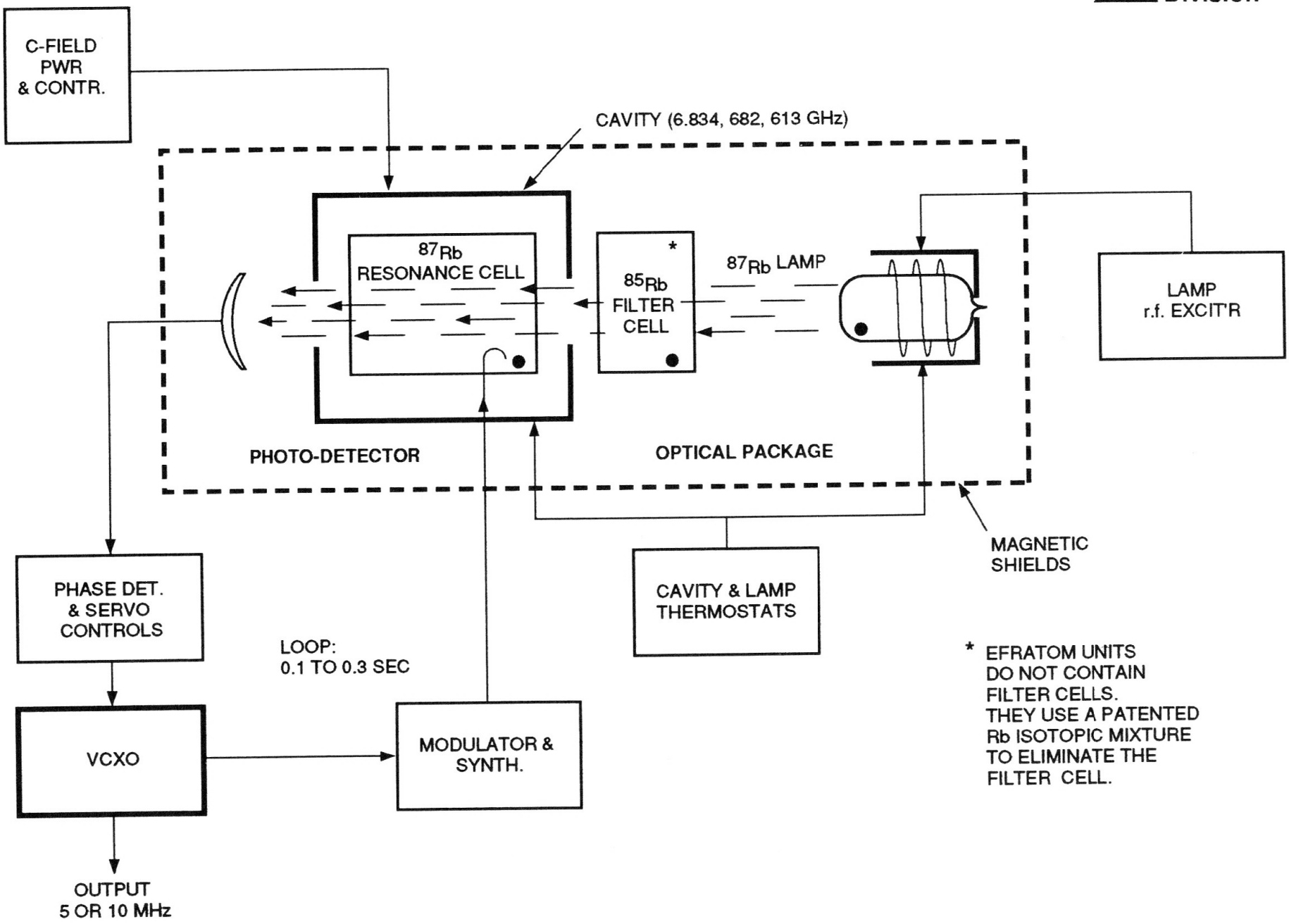
ELECTROMAGNETIC SPECTRUM

Ball Efratom Division



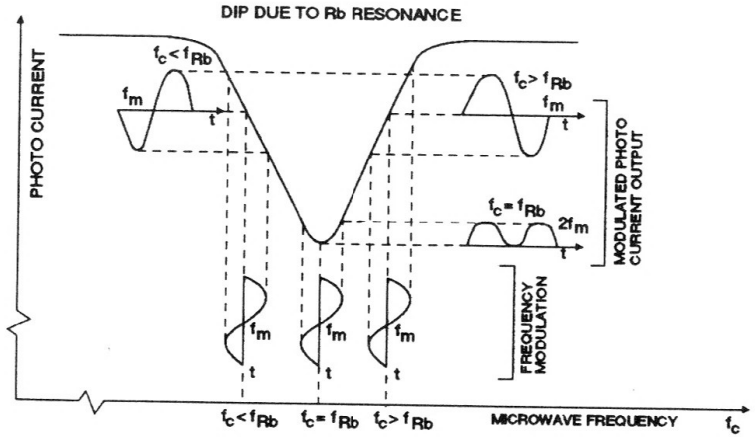
BASIC RUBIDIUM OSCILLATOR CONCEPT

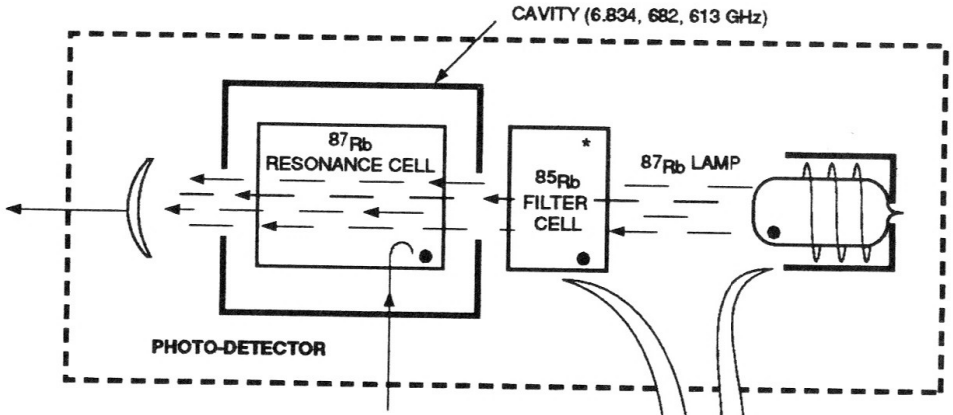
Ball Efratom Division

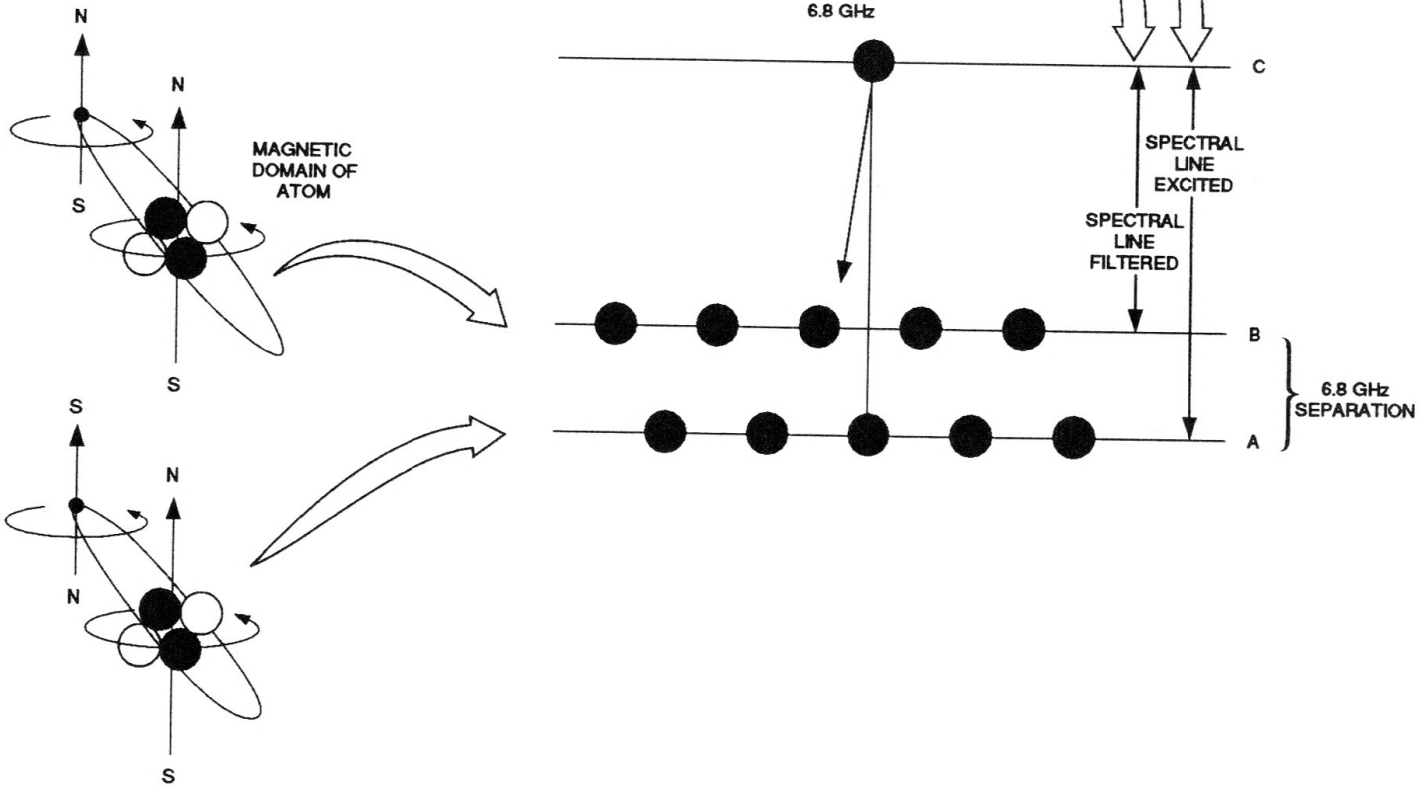


OPTICAL PUMPING PROCESS

Ball Efratom Division

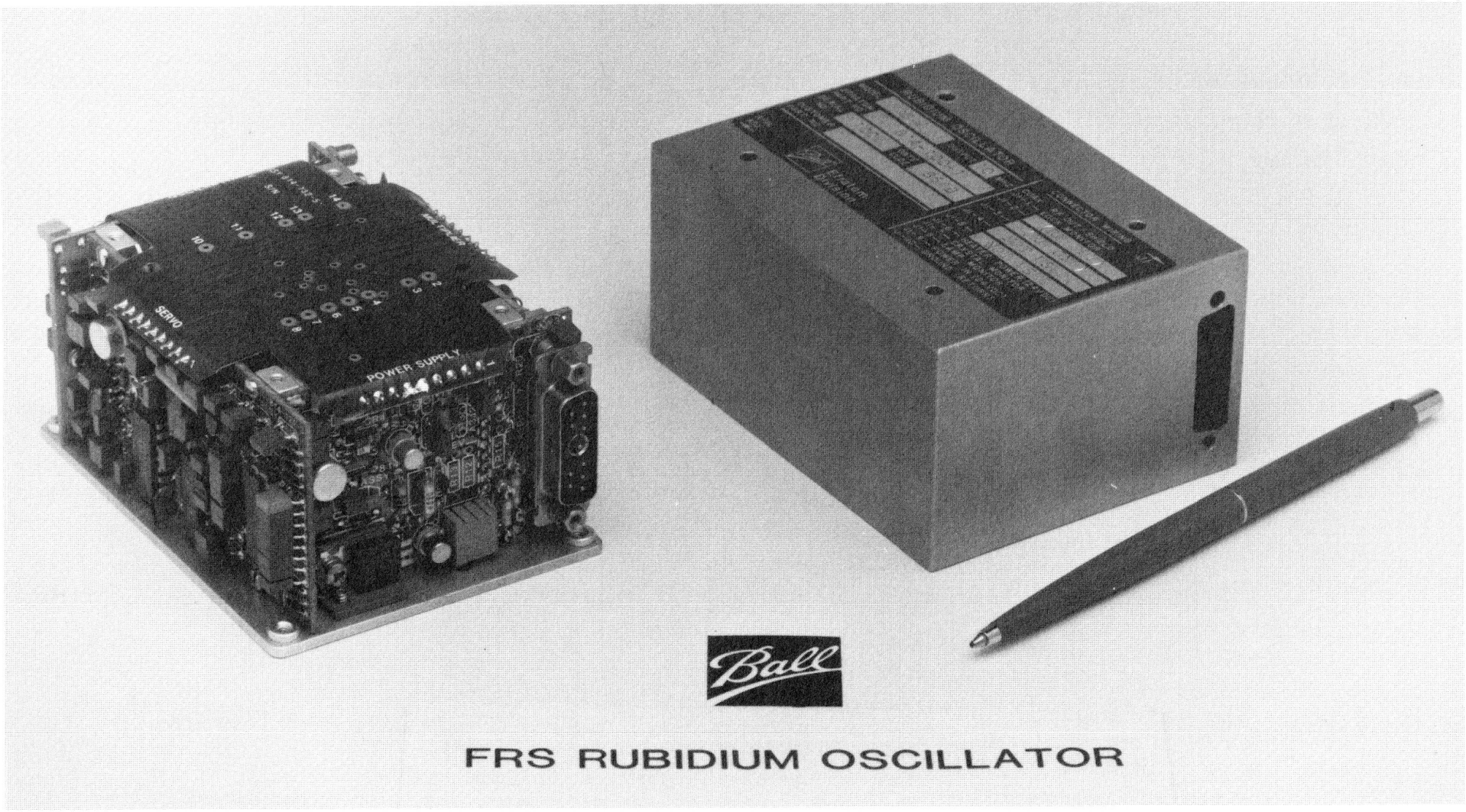




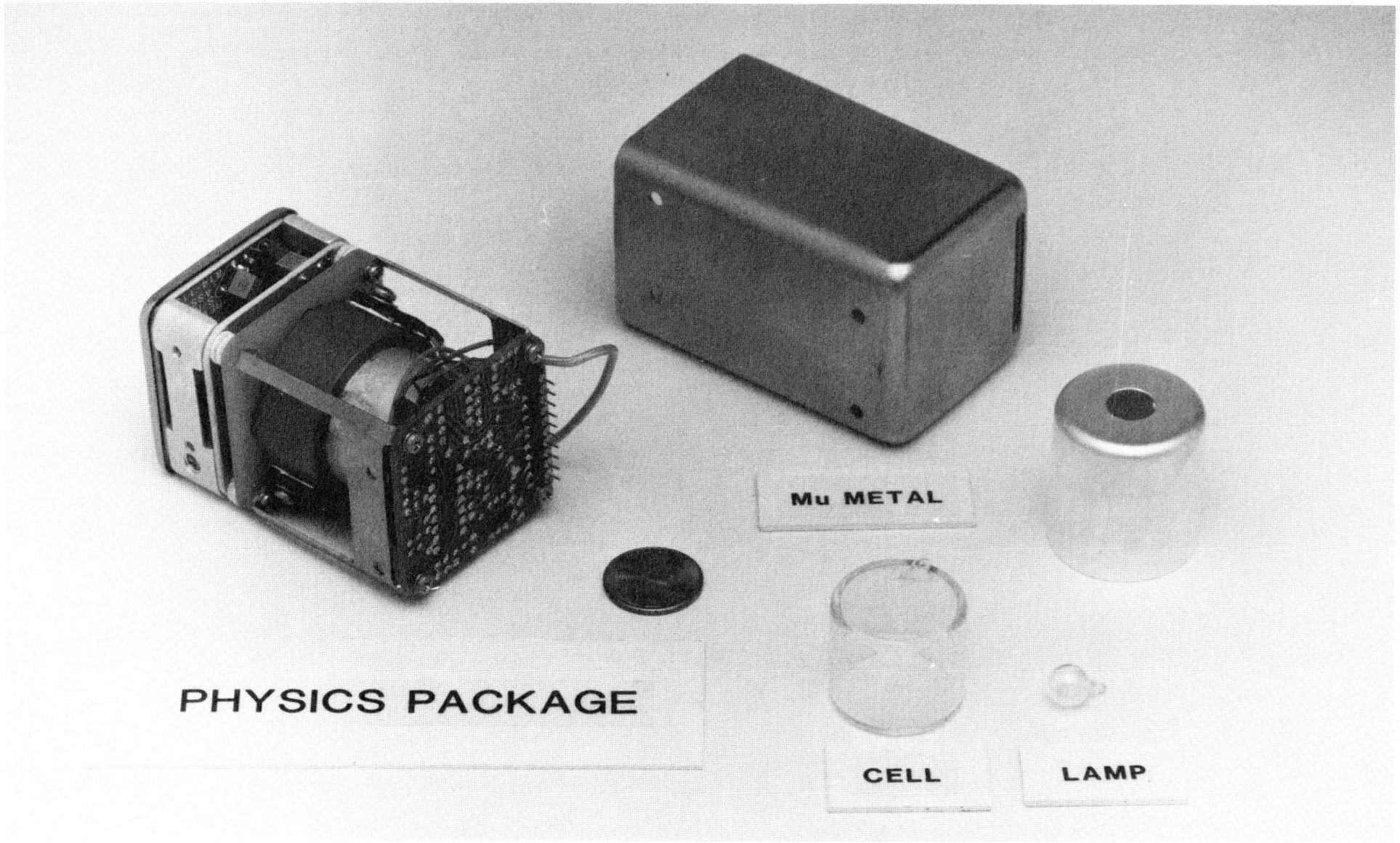


MODEL FRS RUBIDIUM OSCILLATOR

Ball Efratom Division



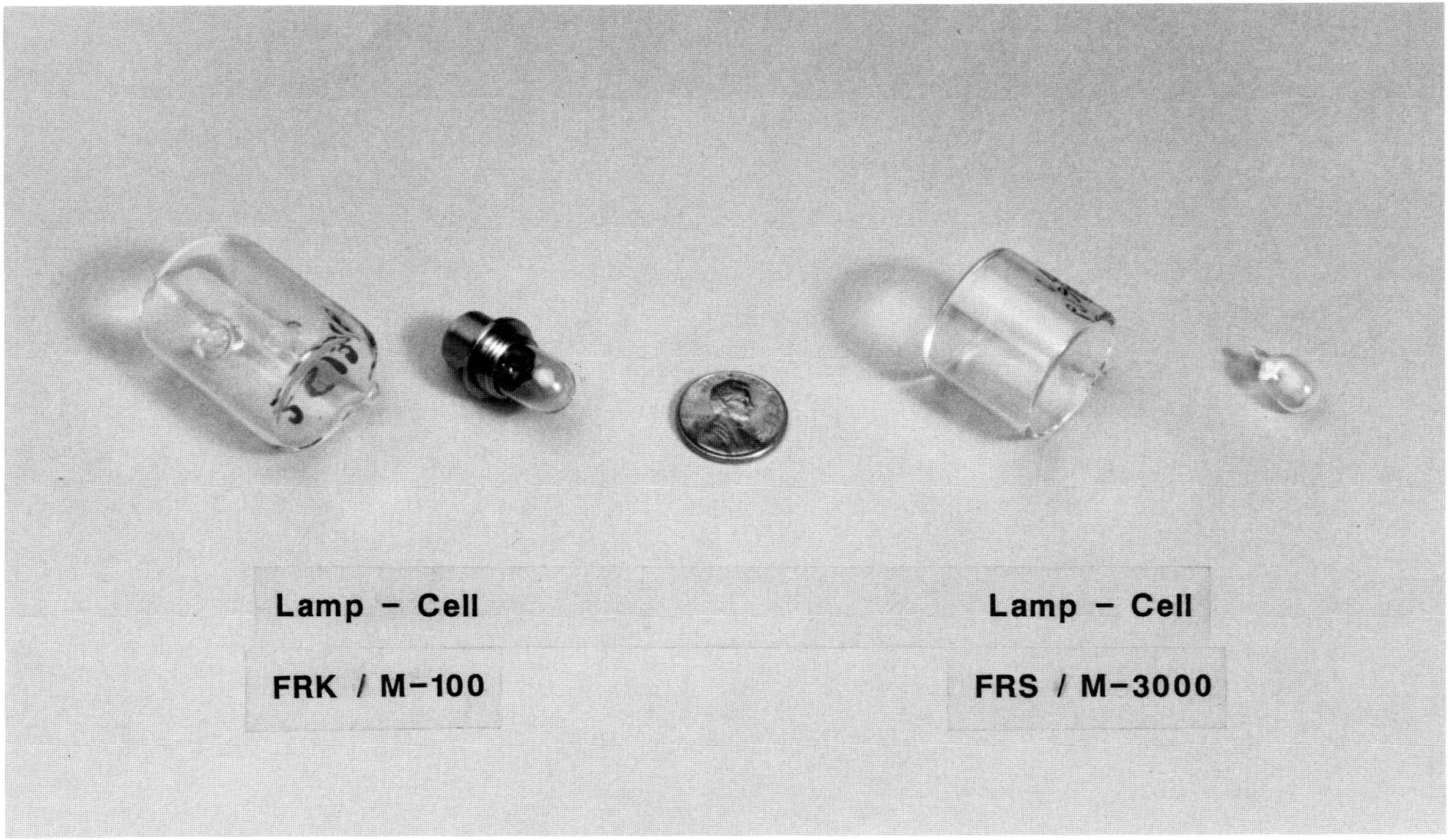
Ball Efratom Division



FRS RUBIDIUM OSCILLATOR

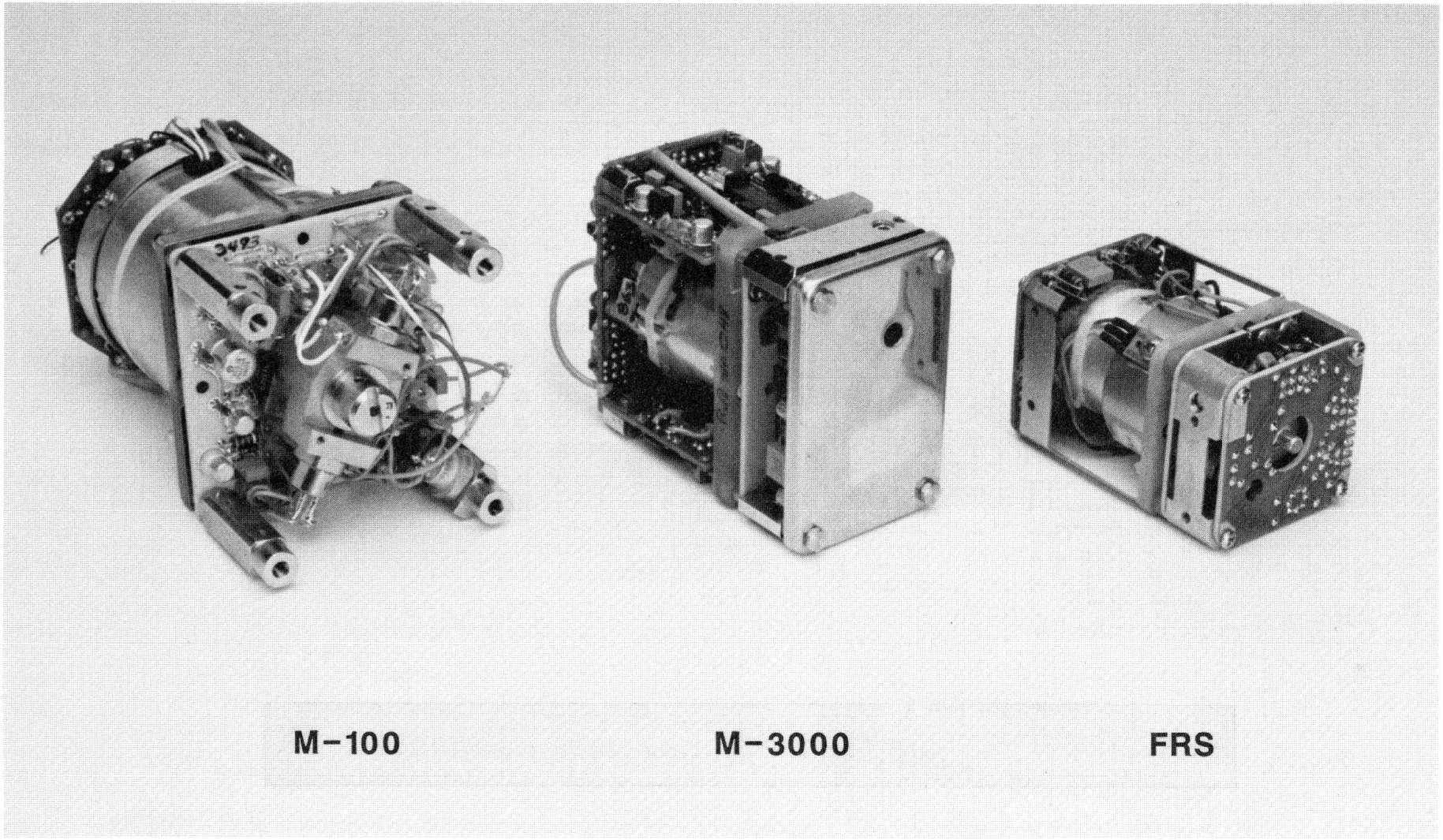
RUBIDIUM PHYSICS PACKAGE COMPONENTS

Ball Efratom Division



PHYSICS PACKAGES

Ball Efratom Division



M-100 M-3000 FRS

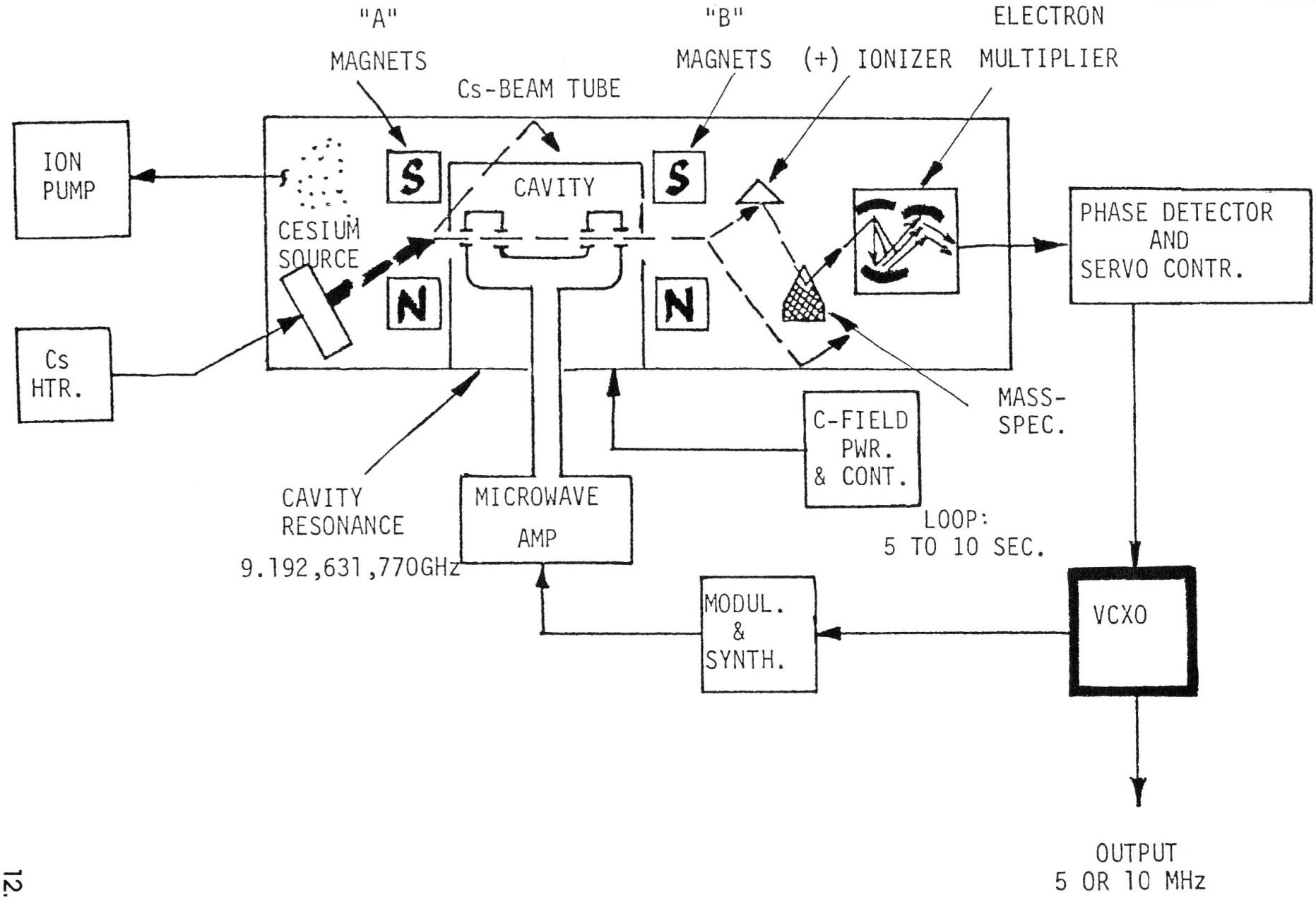
THE RUBIDIUM ATOMIC OSCILLATOR

Advantages	Disadvantages
· Short Warm-Up Time	· Has Frequency Aging vs. Cesium
· Good Re-Trace	· Temperature Coefficient vs. Cesium
· Low Sensitivity to Radiation	· Power Consumption vs. Quartz
· Low Linear Acceleration Sensitivity	
· Small Size and Atomic Precision	
· Low Weight	
· Low Cost	
· Very Tactical / Mobile	

The essential elements of the Atomic Physics Package can be made quite small, approximately 1 x 2 in. (2.5 x 4.1 cm). This, coupled with a less sophisticated crystal that eliminates complex thermal controls and insulation, makes it possible for the entire rubidium oscillator package to be similar in size to a stand-alone high performance quartz crystal oscillator of about 3 x 3 x 4.5 in. (7.6 x 7.6 x 11.4 cm). The smallest of these rubidium oscillators is the Efratom Model FRS, 2 x 3 x 4 in.

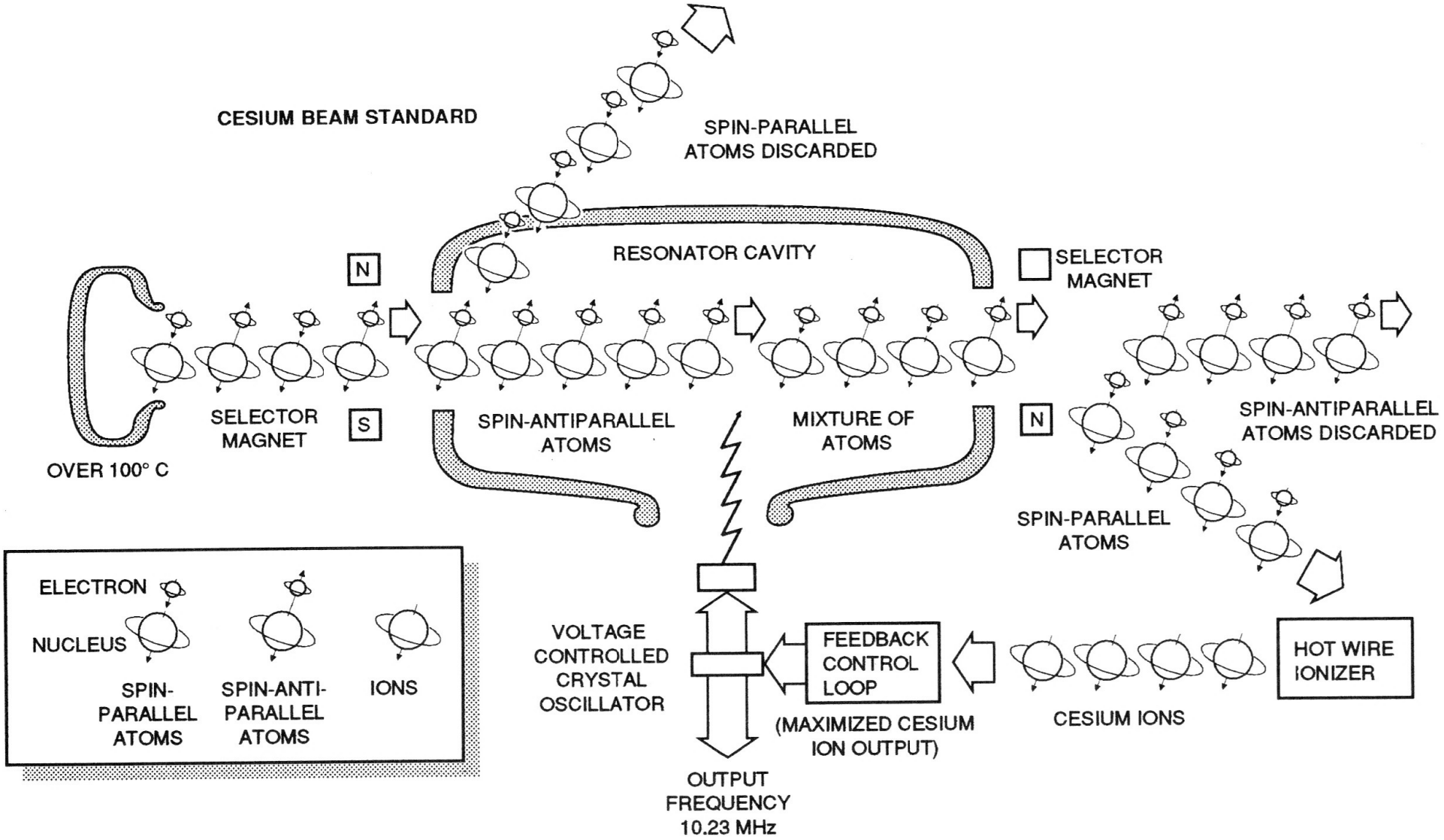
BASIC CESIUM-BEAM OSCILLATOR CONCEPT

Ball Efratom Division



BASIC OPERATION OF A CESIUM ATOMIC OSCILLATOR

Ball Efratom Division



Courtesy of Tom Logsdon, Rockwell International

THE CESIUM ATOMIC OSCILLATOR

Advantages	Disadvantages
· No Frequency Aging, A Primary Standard	· Temp. OPS Range
· Small Temperature Coefficient	· Long Warm-Up Time
· Good Radiation Performance	· Physics Tube Wears Out
· Low Sensitivity to Altitude External and Magnetic Fields	· Not Very Tactical
	· Large Size, Weight
	· High Cost

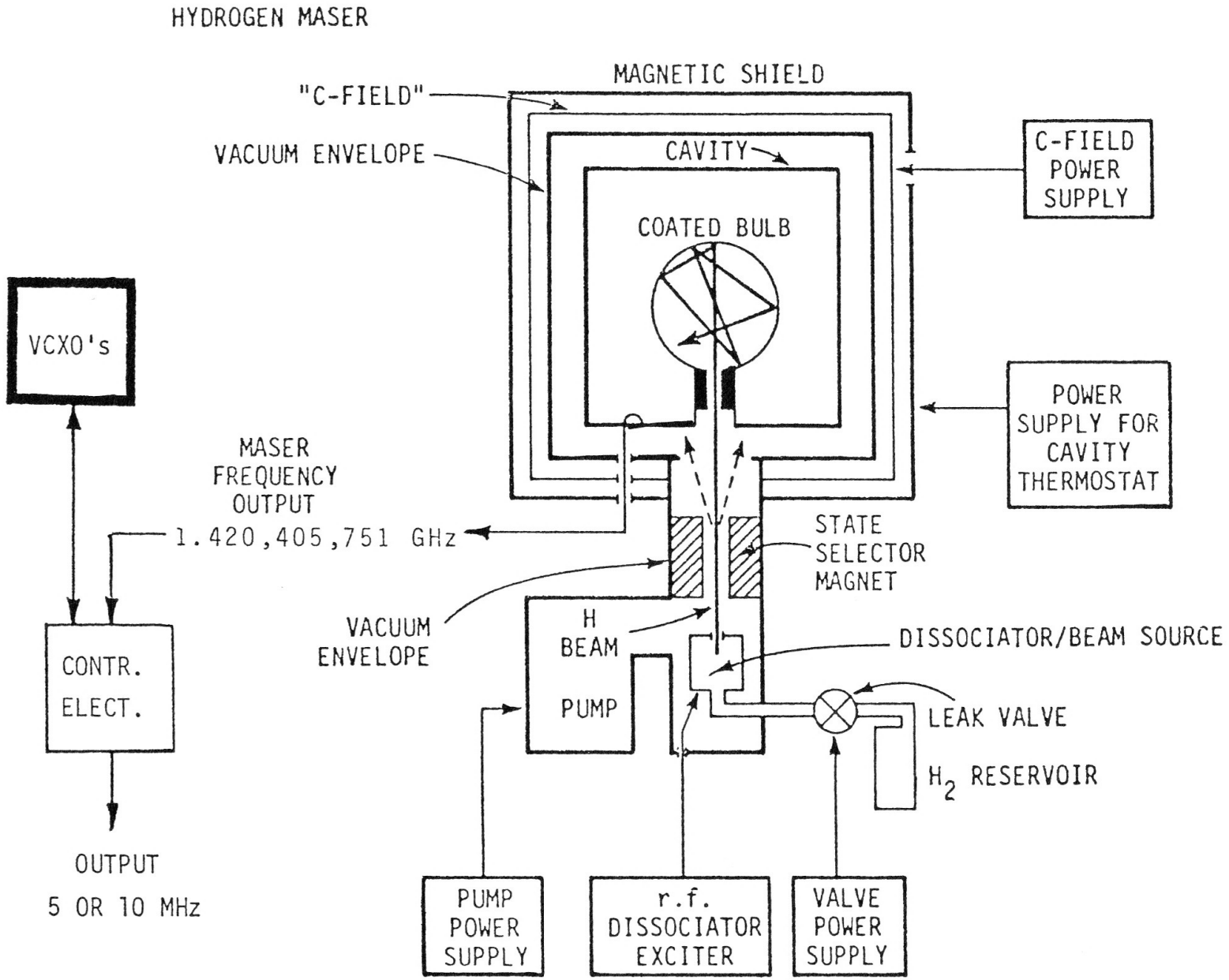
The cesium oscillator physics package cannot be made as small as the rubidium physics due to beam travel constraints, cavity size, selector magnets, etc. It is limited at best to 6 to 9 in. in length and approximately 3 to 4 in. diameter (15.2 x 7.6 cm).

THE HYDROGEN MASER ATOMIC OSCILLATOR

The hydrogen maser (maser is an acronym that stands for Microwave Amplification by Stimulated Emission of Radiation) differs from the atomic oscillators discussed so far in that it can be operated as a self-sustaining microwave oscillator that oscillates at the atomic hyperfine frequency (1.420 403...GHz for hydrogen). A maser oscillating in this fashion is referred to as an "active" maser, in contrast to the "passive" operation of the rubidium and cesium devices already described. With an active device, the output signals can be derived more directly from the atomic resonance. This provides for an additional characteristic superior to those of rubidium and cesium units, in that the crystal oscillator is phase-locked to the maser signal. This locks both short and long-term performance characteristics of the crystal with a near zero loop constant, thus eliminating the previously discussed crystal-only performance for a time period shorter than the loop time. The bulb is analogous to the gas cell and beam tube oscillators. It is in this container that the transition of hydrogen atoms between the two pre-selected for ground state hyperfine energy levels is induced.

BASIC ACTIVE H-MASER CONCEPT

Ball Efratom Division



THE HYDROGEN MASER ATOMIC OSCILLATOR (CONT.)

Molecular hydrogen coming from a simple pure hydrogen source is first dissociated by an electrical discharge and the resultant atomic hydrogen is collimated into a beam. The beam is directed into a magnetic field which discards atoms of one hyperfine energy level and passes atoms of the other. The selected atoms are then directed into the storage bulb located in an rf cavity, where interaction with a microwave field at the resonator frequency takes place. This transition frequency is approximately 1.4 GHz. The bulb is designed to allow extremely long interaction times of atoms and the microwave field by coating the walls to reduce atom perturbations through wall collisions.

The interaction with the microwave field induces the hydrogen atoms in the selected energy state to make a transition to the lower state, thus radiating energy to the field. Maser oscillations are self-sustaining when the atom density in the storage bulb is such that the resulting induced transitions radiate enough coherent energy to more than offset cavity losses.

THE HYDROGEN MASER ATOMIC OSCILLATOR (CONT.)

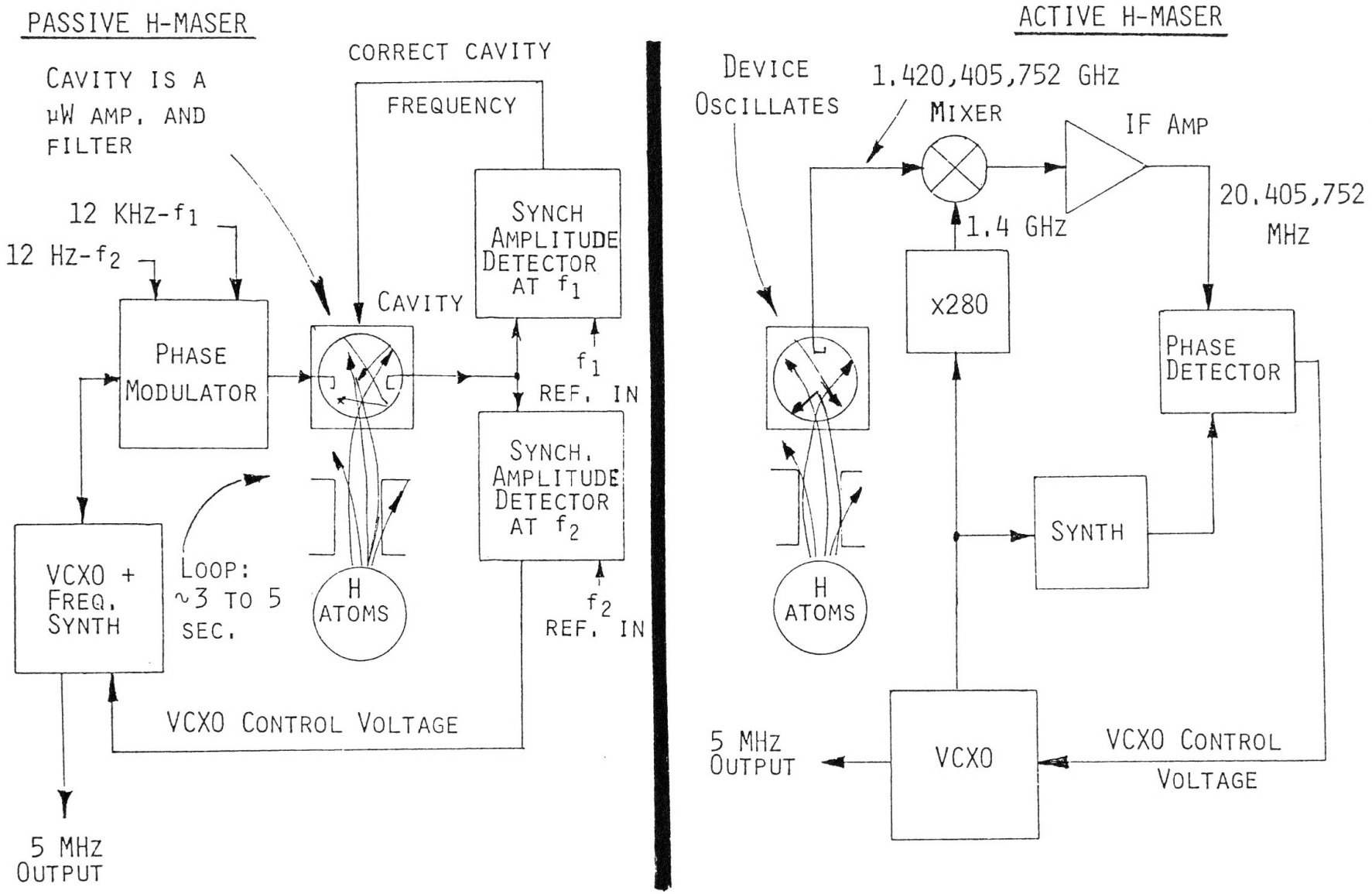
In the passive hydrogen maser, virtually all the atomic functions are the same as for the active maser, except for the following:

(A) The atoms are not self-oscillating but act as a tank, performing microwave amplification and filtering of interrogating microwave resonant frequencies introduced into the cavity. As a result, the passive operation is similar to that of rubidium and cesium oscillators.

(B) The crystal oscillator is servo'd through the error signal generated by the passive resonance detection and thus is not phase locked to a self-oscillating cavity; the short-term frequency stability of the passive hydrogen maser is therefore not as good as that of the active maser but is still superior to that of rubidium and cesium oscillators.

ACTIVE vs. PASSIVE H-MASER

Ball Efratom Division



THE HYDROGEN MASER ATOMIC OSCILLATOR

Advantages	Disadvantages
· Best Overall Stability/ Performance From $T = 10^0$ sec. To $T = 10^6$ sec. Averaging Time	· Has Frequency Aging (Certainly Parts in 10^{15}/Day)
· A Factor of 3 To 5 Times Better Stability Than High Performance Option Cesium Standards	· Not a Primary Standard (Although could be called such)
	· Long Warm-Up Time
	· Poorest MTBF of all Atomic stds.
	· Largest Size, Weight
	· Highest Cost

In general, the passive maser concept lends itself to size reduction and mass production more readily than its active counterpart, and may well be the choice of super-precision frequency standards for the next 10 to 20 years. The passive hydrogen maser is larger than all other types of atomic oscillators- about 19 in. wide (for rack mounting) by 10 in. high (48.3 x 25.4 cm)- but is still size competitive with cesium oscillators.

GENERAL COMPARISON OF PRECISION OSCILLATORS

Stability versus averaging time for the precision oscillators is presented in the next figure. The flat portions of the lines represent the noise floors the oscillators will reach. The up-turn of the quartz crystal and rubidium lines is the result of aging and random walk.

Specifications and important considerations for each type of oscillator are shown in the following table. The quartz crystal oscillator in the table is of the precision class and not representative of common crystal oscillators produced by the millions. Costs reflect quantity procurements.

- Quartz Crystal Oscillator. The advantages of present commercial quartz oscillators are small size, light weight, and low power consumption. Although there appear to be cost advantages for the hardware, when coupled with calibration intervals that are more frequent than for atomic oscillators, the cost advantages over rubidium are questionable. For systems in which size, weight, and power consumption are most important, and where aging and retrace disadvantages can be tolerated, the quartz oscillator is the proper choice. If rapid warm-up is needed and the equipment will be operated in a hostile environment, these advantages may be negated.

- Rubidium Oscillator. The advantages are small size and light weight (for an atomic oscillator), medium power requirements, and extremely fast warm-up. These advantages, coupled with good performance in hostile environments, make the rubidium oscillator the first choice for mobile and tactical systems. It has no major disadvantages except aging of parts in 10^{10} per year.

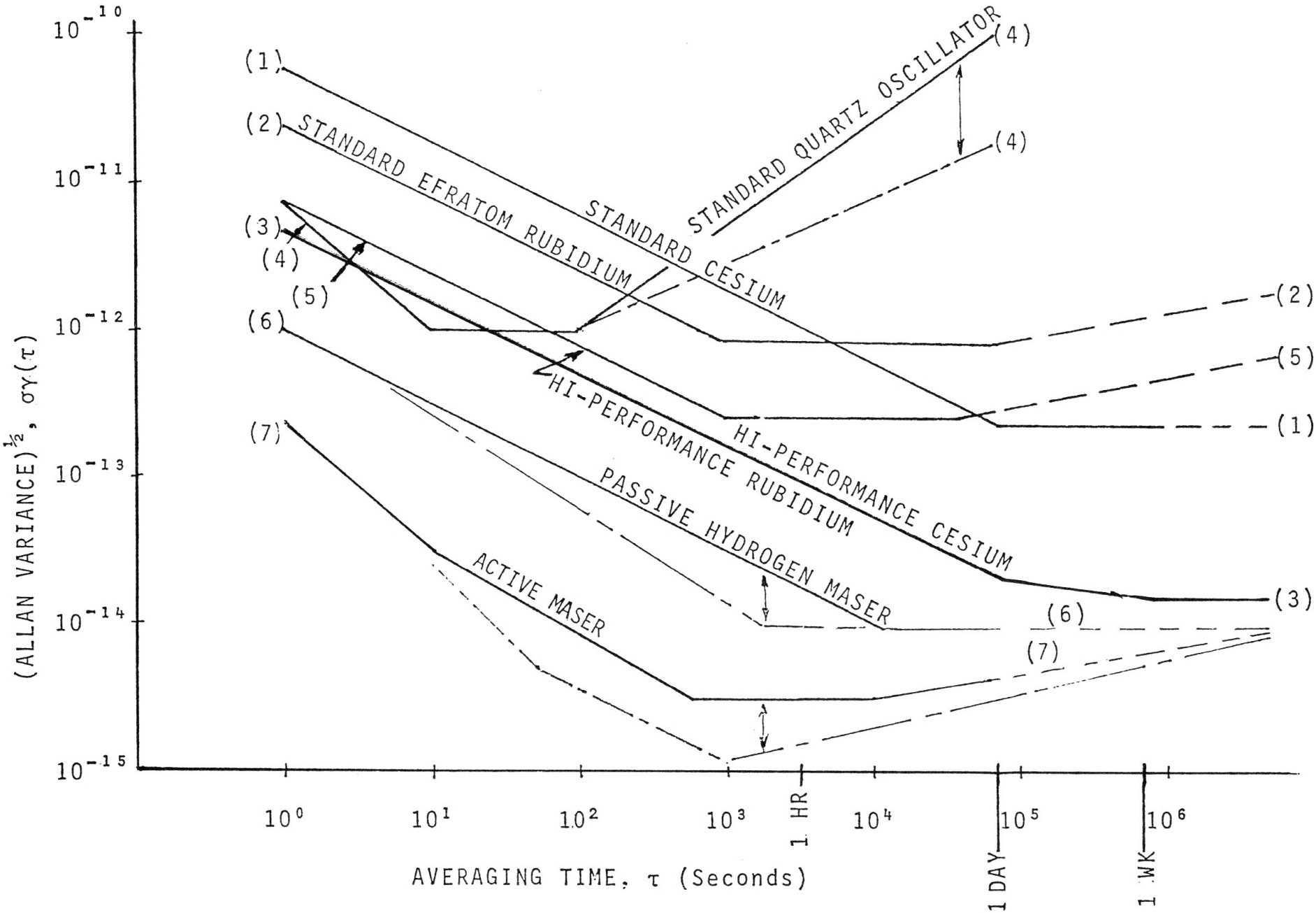
GENERAL COMPARISON OF PRECISION OSCILLATORS (CONT.)

Cesium Oscillator. The advantages are excellent long-term stability, no aging, little need for calibration, and high tolerance of hostile stationary environments. (Hostile dynamic environments are not well tolerated, however.) The large size, weight, higher power, and cost make the cesium oscillator more useful in stationary and benign environmental applications such as providing a reference against which other, less stable oscillators would be periodically checked. Where space and power are not at a premium, such as ships, large aircraft, ground stations, and laboratories, the cesium oscillator is the best choice.

Hydrogen Masers. The advantages are extremely high stability; better than the best cesium oscillators. This performance is realized from the short-term (subseconds) to days, weeks, and months, outperforming cesium oscillators even on a yearly basis. Its large size, weight, power requirements, and medium tolerance of hostile environments, relegate it to a more stationary environment. It is a good choice in cesium oscillator applications where the short-term performance of cesium is inadequate.

GENERAL COMPARISON OF HIGH-PERFORMANCE OSCILLATOR FREQUENCY STABILITY (TYPICAL)

Ball Efratom Division



GENERAL COMPARISON OF HIGH-PERFORMANCE OSCILLATORS (CONT.)

Ball Efratom Division

DESCRIPTION	EFRATOM NEW EMXO	HIGH-PRECISION QUARTZ OSC.	EFRATOM RUBIDIUM OSC.	COMMERCIAL CESIUM BEAM	HYDROGEN MASER
PRIMARY STANDARD	NO	NO	SECONDARY 6.834, 682, 613 GHz	YES 9.192, 631, 770 GHz	NO 1.420, 405, 751 GHz
FUNDAMENTAL WEAROUT MECHANISM	NONE	NONE	LAMP LIFE (15 YEARS +)	Cs CONTAMINATION OF ELECTRON MULT. (5 YEARS +)	ION PUMPS AND H2 SOURCE DEPLETION (5 YEARS +)
PORTABILITY, APPLICATION	EXTREMELY PORTABLE	VERY PORTABLE SPACE-AIR-GROUND	VERY PORTABLE SPACE-AIR-GROUND	MORE GROUND AND LAB ORIENTED	DEFINITELY MORE GRD. AND LAB USE
APPROX: SIZE WEIGHT POWER COST	1.3" X 1.3" X 1.3" 0.09 LBS. 0.3-0.75 WATTS $1.0 K TO $2.0 K	~3" X 3" X 3" 1-2 LBS. 2-5 WATTS $2.0 K TO $4.0 K	~3" X 3" X 4.5" 1.2 TO 4 LBS. 10-18 WATTS $3.0 K TO $8.0 K	19" RACK, 6" H 25-70 LBS.* ~25-35 WATTS $50 K TO $65 K	19" RACK, 10 TO 20" H ~120 LBS. ~100 WATTS $100 K TO $250 K
SHORT-TERM STAB. t=1 SEC.	1 TO 5E-12	PARTS IN $10^{12}/10^{13}$	1 TO 3E-11	1 TO 7E-11 5E-12 *	<2E-12
STABILITY AT 1 DAY	PARTS IN 10^{10}	PARTS IN 10^{10}	1E-12/1E-13	2E-13 3 TO 5E-14 *	<1E-14 TO 2E-15
AGING/DAY	1 TO 5E-10	1E-10/1E-11	PARTS IN 10^{13}	NONE	PARTS IN 10^{15}
ACCURACY/YEAR**	PARTS IN 10^{7}	<1E-7	1E-9/1E-10	<1E-11	<2E-13
TEMPERATURE COEFFICIENT	± 5E-9 -55°C TO +90°C	PARTS IN 10^{9} -55°C TO 65°C	PARTS IN 10^{10} -55°C TO 71°C	PARTS IN 10^{11} -25°C TO 65°C	<5E-14/°C 0°C TO 50°C
RETRACE	PARTS IN 10^{9}	PARTS IN 10^{9}	~1E-11	~1E-11	<5E-14
WARM-UP TIME	<4 MIN. TO 1E-8	10 TO 60 MIN. TO PARTS IN 10E8	~2.5 TO 5 MIN. TO 5E-10	30 MIN. TO 3 TO 5E-12	24 HOURS TO 1E-12

*HI-PERF. OPTION

THE FUTURE OF PRECISION OSCILLATORS

The Quartz Crystal Oscillator for high-performance applications will remain about the same volume and may enjoy a factor of 10 improvement in some of the parameters listed. Considering the fact that more precise manufacturing techniques will be needed to realize these improvements, one could expect the relative cost to increase.

The Rubidium Oscillator can be expected to continue to shrink in size due to further reduction in physics package volume and more electronic miniaturization. Performance parameters expected to improve, possibly a factor of 5 to 10, are: temperature coefficient, pressure sensitivity, and vibration performance. No increase in precision of manufacturing techniques is needed. This, coupled with an enormous demand expected in the net 10 to 30 years, should lower the relative cost per unit.

The Cesium Oscillator performance can be expected to remain as presently available. A size reduction is possible due to new physics improvements; no major changes in performance and price are expected. Possible improvements in beam tube life may be realized and units may be made more tactical.

The Active and Passive Hydrogen Masers are expected to make a future impact. They outperform the high-performance cesium oscillators for a time period of sub-seconds to months, equalling cesium at the 1, 2 or more year period. The price for the passive maser is expected to be near the high-performance cesium option and the active maser will cost two times that of the passive maser.

FUTURE OF PRECISION OSCILLATORS

Ball Efratom Division

	DESC.	QUARTZ OSC.	RUBIDIUM OSC.	CESIUM OSC.	PASSIVE HYDROGEN-MASER
PRESENTLY ON MARKET	CAN BUY	TCXO'S, OCXO'S - PARTS IN $10^6/10^8$/YR - PARTS IN $10^6/10^6$ Tc -PARTS IN $10^9/10^{10}$/G -10 TO 500 cm^3	MINIATURE Rb OSC. - PARTS IN $10^9/10^{10}$/YR - PARTS IN 10^{10} Tc -PARTS IN 10^{12}/G -375 TO 1000 cm^3 -FRS (24 $in.^3$, 375 cm^3)	- 19 IN. RACK UNITS - VARIOUS STABILITY OPTIONS	- NONE; WILL APPEAR IN 1992 TIME FRAME
FUTURE	CAN EXPECT	- MORE FANCY DOUBLE ROTATED CUTS - BETTER AGING	- SMALLER PHYSICS - MORE ELECTRONIC MINIATURIZATION	- SOME SIZE REDUCTION - LONGER TUBE LIFE	- SOME SPEC IMPROVEMENTS - RELIABILITY IMPROVEMENTS
	SIZE	- SMALLER PACKAGE - TMXO, EMXO, 7.5cm^3 (300 MW @ 25°C)	- SMALLER UNITS IN 1993?	- 1/2 - 19" RACK WITH OPTICAL PUMPING	- 19" RACK, 10" HIGH ~120 LBS. ~100 WATTS
	ACCEL.*	P10 ^{9}vs. P10 ^{11}/G	P10 ^{12}/G NOW	NO CHANGE	N/A
	RETR.	P10 ^{9}vs. P10 ^{10}	P10 ^{11} NOW	NO CHANGE	<5E-13
	AGING	P10 ^{10}vs P10 ^{11}/DAY	P10 ^{13}vs. P10 ^{14}/DAY	NONE	P10 ^{15}
	WARM-UP	HRS vs. MIN TO P10 ^{9}	2.5 MIN TO P10 ^{10} NOW	HRS vs. MIN TO P10 ^{12}	24 HRS TO 1E-12
	TEMP-K	P10 ^{8}vs. P10 ^{9} OVER RANGE	P10 ^{10}vs. P10 ^{11} OVER RANGE	NO CHANGE	<5E-14/°C
	PRESS.	N/A	P10 $^{-11}$ vs. P10 ^{12} (S.L. TO 40 K FT.)	NO CHANGE	TBD
	VIB.	P10 ^{9} vs. P10 ^{11}/G	SAME AS XTAL	SOME IMPROVEMENT	N/A
	COST	NO CHANGE; POSSIBLY HIGHER	WILL GO LOWER	NO CHANGE	WILL GO LOWER

TIME & FREQUENCY TRANSFER

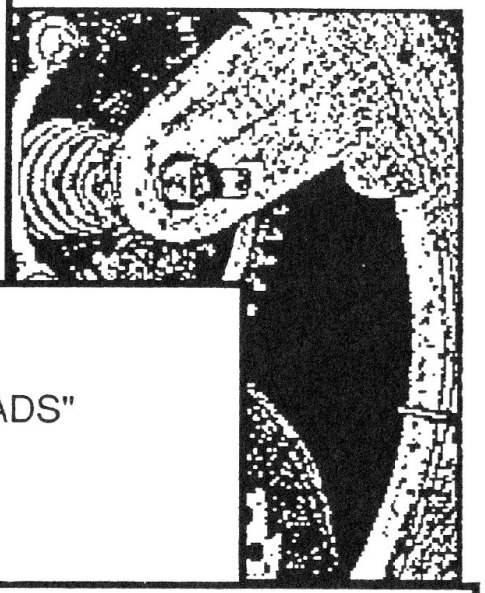
WHAT IS TIME?

Ball Efratom Division

"WHAT THEN IS TIME? IF SOMEONE ASKS ME, I KNOW; IF I WISH TO EXPLAIN IT TO SOMEONE WHO ASKS, I KNOW NOT".

BISHOP OF HIPPO

NORTH AFRICA 5th CENTURY A.D.



"TIME IS WHAT A CLOCK READS"

ALBERT EINSTEIN

"THE CLOCK, NOT THE STEAM ENGINE IS THE KEY MACHINE OF THE INDUSTRIAL AGE".

LEWIS MUMFORD*

TECHNICS & CIVILIZATION

*U.S. Social critic and teacher; Stanford; U. of Pennsylvania; M.I.T.; Wesleyan U.; (born 1895)

Courtesy of Tom Logsdon, Rockwell Int'l

PAST, PRESENT AND FUTURE OF ATOMIC TIMEKEEPING

...TAKEN IN PART FROM A BRIEFING GIVEN BY NOBEL PRIZE WINNER IN PHYSICS, DR. NORMAN RAMSEY (AT NOVEMBER 1990 PTTI MEETING IN WASHINGTON DC)

PAST, PRESENT, AND FUTURE OF ATOMIC TIMEKEEPING

THE PAST

1911 - First Atomic Beam (Dunoyer)

1921 - Deflection of Atomic Beam by Inhomogenous Magnetic Field (Stern)

1933 - Deflection of Light by Photon Absorption (Frisch)

1938 - Molecular Beam Magnetic Resonance Method for Measuring Nuclear Magnetic Moments (Rabi, Zacharias, Millman, & Kusch)

1939 - Radio Frequency Spectroscopy (Kellogg, Rabi, Ramsey, and Zacharias)

1940 - Atomic Hyperfine Structure, Field Independent Oscillations, Discussion of Atomic Clocks...(Rabi, Kusch, Millman...)

1949 - Method of Separated Oscillatory Fields: Narrower resonances, Higher Frequencies, No First Order Doppler (Ramsey)

1950 - Optical Pumping (Kastler)

1952 - Initial Work on Cs Clock (Kusch, Lyons, Sherwin)

1953 - Unsuccessful Atomic Fountain

1954 - Atomichron (Zacharias)

PAST, PRESENT, AND FUTURE OF ATOMIC TIMEKEEPING

THE PAST (continued)

1955 - Atomic Cs Beam Frequency Standard (Essen & Parry)

1958-1961 - Microwave Spectroscopy (Townes), Optical Pumping (Hastler,...), Buffer Gases (Dicke,lll), NH_3 Maser (Townes,...), Optically Pumped Rb Frequency Standards...

1959 - Ion Traps (Penning, Paul, & Dehmelt). Initially Large Doppler Shifts and Widths.

1960 - Lasers (Townes, Schawlow, Maiman). Suppression of First Order Doppler by Two Photon Absorption Spectroscopy,..., Frequency Chains for Calibration.

1960 - Improvements In All Frequency and Time Standards.

1962 - Hydrogen Maser (Kleppner, Ramsey,...)

1968 - Cooling of Trapped Ions By The ^4He (Dehmelt, Cutler)

*1969 - Small, Integrated Cavity Rubidium Oscillator & Rb Isotope Mixture, Efratom Elektronik GmbH (Jechart, Huebner)

1975 - Electron Shelving With Many Trapped Ions As An Amplification Mechanism To Detect Weak Transitions By Monitoring Affected Resonance Fluorescence.

13

*Added to Dr. Ramsey's Briefing

PAST, PRESENT, AND FUTURE OF ATOMIC TIMEKEEPING

THE PAST (continued)

1975 - Laser Cooling (Wineland, Dehmelt, Hansch, Scawlow)

1980 - Laser Cooling of Trapped Ions (Wineland, Bergquist, Drullinger, Itano, Dehmetlt, Toscheck,...)

1981 - Single Atomic Ion Trapping And Cooling. Quantum Jumps And Electron Shelving With Single Ions (Dehmelt, Wineland,...)

1985 - Slowing of Neutral Atoms (Phillips, Metcalf, Letokhov, Hall, Weiman)

1985 - Optical Molasses And Stimulated Molasses (Chu,... Cohentannoudji,...)

1985 - Laser Trapping Of Atoms, Gradient Traps And Spontaneous Radiation Traps (Chu, Pritchard, Weiman, Aspect Dalibard, Cohen-Tannoudji, Metcalf,...)

1988 - Sympathetic Cooling (Larson, Wineland,...)

1988 - Cooling Below Doppler And Recoil Limits. Polarization Gradient Cooling. Sisyphus Effect. Velocity Selective Coherent Trapping. 5.2u. (Phillips, Chen-Tannoudji, Dalibard, Chu, Metcalf,...)

1989 - Successful Fountain Experiment (Chu,...)

PAST, PRESENT, AND FUTURE OF ATOMIC TIMEKEEPING

THE PRESENT

- Atomic Time And Frequency Standards In Extensive Actual Use

- Low Cost
  Optically Pumped Rb

- High Accuracy
  Cs Atomic Beam...10^{-13}

- Highest Stability
  Atomic Hydrogen Maser...10^{-15}

- High Frequency
  Lasers

- Many Promising Developments

PAST, PRESENT, AND FUTURE OF ATOMIC TIMEKEEPING

THE FUTURE
UNRELIABILITY OF PREDICTIONS

- Improvements In All Devices

Optically Pumped Rb Cells - Better Wall Coatings, Omission Of Buffer Gas, Other Atoms.

Atomic Beam - Different Atoms Or Molecules, Higher Frequency, Two Beams In Opposite Directions To Cancel Phase Shifts. Optical Pumping. State Selection And Detection By Laser Beams. Better Velocity Selection To Reduce Second Order Doppler Broadening, Better Flywheel Oscillators Of High Short Term Stability - High Q And Super Conducting Cavities, Circuits With Optical Or Electrical Feedback From High Q Cavity, Use of H-Maser As Flywheel Oscillator.

Atomic Hydrogen Maser - Electronic Cavity Tuning, Elimination Of F=0 State, Cryogenic Temperatures, New Wall Coatings Such As Superfluid ^{4}He, Fomblin Oil, (Diamond,...)

DEFINITION OF TERMS FOR TIME & TIME TRANSFER [1]

Universal Time (UT)

Universal Time (UT) is the general designation of time scales based on the rotation of the earth. (GMT may be regarded as the general equivalent of UT.)

In applications in which an imprecision of a few hundredths of a second cannot be tolerated, it is necessary to specify the form of UT which should be used:

UT0 is the mean solar time of the prime meridian obtained from direct astronomical observation;

UT1 is UT0 corrected for the effects of small movements of the earth relative to the axis of rotation (polar variation);

UT2 is UT1 corrected for the effects of a small seasonal fluctuation in the rate of rotation of the earth.

Coordinated Universal Time (UTC)

The time scale maintained by the BIH which forms the basis of a coordinated dissemination of standard frequencies and time signals. It corresponds exactly in rate with TAI, but differs from it by an integral number of seconds.

The UTC scale is adjusted by the insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with UT1.

(1) Taken in part from letter by, David Allan, NIST, to CCIR Study Group XII U.S. Committee Members, 3-17-89.

DEFINITION OF TERMS (cont.)

International Atomic Time (TAI)

The time scale established by the Bureau International de Poids de Mesure' (BIPM) on the basis of data from atomic clocks operating in several establishments conforming to the definition of the second, the unit of time of the International System of Units (SI).

Julian date (JD)

The Julian Day Number followed by the fraction of the day elapsed since the preceding noon (12 hours UT).
Example:
The date 1900 January 0.5 d UT corresponds to JD = 2 415 020.0.

Julian day number

A number of a specific day from a continuous day count having an initial origin of 12 hours UT on 1 January 4713 B.C., Julian Calendar (start of Julian Day zero).
Example:
The day extending from 1900 January 0.5 d UT to 1900 January 1.5 d UT has the number 2 415 020.

Leap second

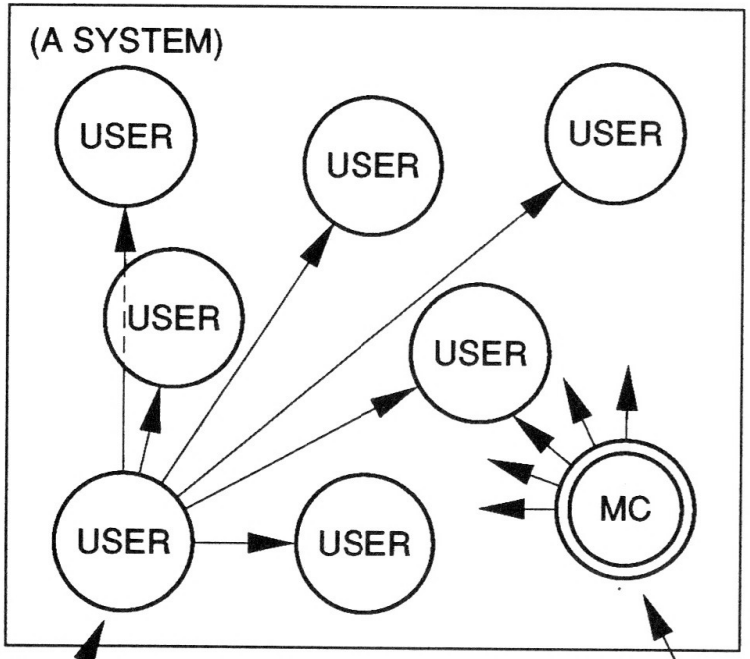
A time step of one second used to adjust UTC to ensure approximate agreement with UT1.
An inserted second is called positive leap second and an omitted second is called negative leap second.

RELATIVE vs. SYSTEMS TIME SYNCHRONIZATION

Ball Efratom Division

IN GENERAL, RELATIVE TIME I REFERS TO TIME SYNC WITHIN THE GROUP OF USERS. SYSTEMS TIME USUALLY REFERS TO TIME SYNC OF THE USER GROUP OBTAINED FROM AN EXTERNAL SOURCE.

RELATIVE TIME

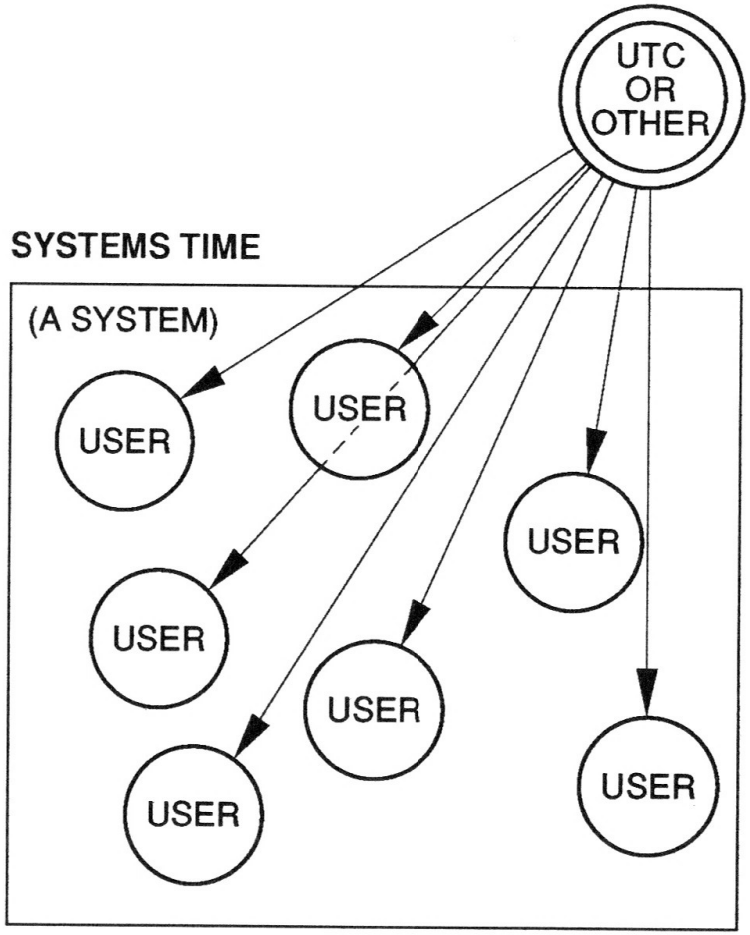


ONE USER CAN BE SELECTED AT RANDOM TO BE THE MASTER FOR THE GROUP

OR

A MASTER STATION WITHIN THE SYSTEM MIGHT BE THE REFERENCE FOR ALL

SYSTEMS TIME



UTC OR ANOTHER EXTERNAL WORLD STANDARD IS THE MASTER FOR THE GROUP

TIME/FREQUENCY TRANSFER VIA PORTABLE CLOCK TECHNOLOGIES

Ball Efratom Division

PARAMETERS	CRYSTAL BASED PORTABLE CLOCKS (BEST CASE)	RUBIDIUM PORTABLE CLOCKS (BEST CASE)	CESIUM PORTABLE CLOCKS (BEST CASE)
FREQUENCY ACCURACY AFTER A 5 HOUR TRIP	~1E-10	~ 1E-11	~1E-12
TIME ACCURACY AFTER A 5 HOUR TRIP	2 TO 5 MICROSEC.	200 TO 300 NANOSEC.	50 TO 100 NANOSEC.
SIZE	1/2-19 INCH RACK	1/2-19 INCH RACK	2-19 INCH RACKS
WEIGHT	15 LBS.	35 LBS.	70 TO 120 LBS.
COST	$10K TO $15K	$18K TO $25K	$35K TO $40K + OPTIONS

TIME TRANSFER VIA NIST GOES SATELLITES

The United States National Institute of Standards and Technology (NIST) (formerly NBS) sponsors a satellite disseminated time code using the Geostationary Operational Environmental Satellites (GOES).

Operated by the National Oceanic and Atmospheric Administration (NOAA), these geostationary satellites transmit a time code referenced to Coordinated Universal Time (UTC). This time code is continuously available to the entire Western Hemisphere.

The time code was initially included in the GOES transmissions to add the time and date to the data collected by remote sensor to make such data more useful. This time code (along with other data used by NOAA's remote sensors) is sent to the GOES satellites from Wallops Island, Virginia. NIST maintains atomic clocks, referenced to UTC, on-site, to generate this time code.

The time code is time-division-multiplexed with interrogation messages to remote data collection platforms. Once every half-second a time code word of four bits is transmitted. A complete time-of-year time code transmission requires 11 seconds to complete, and is repeated every 30 seconds.

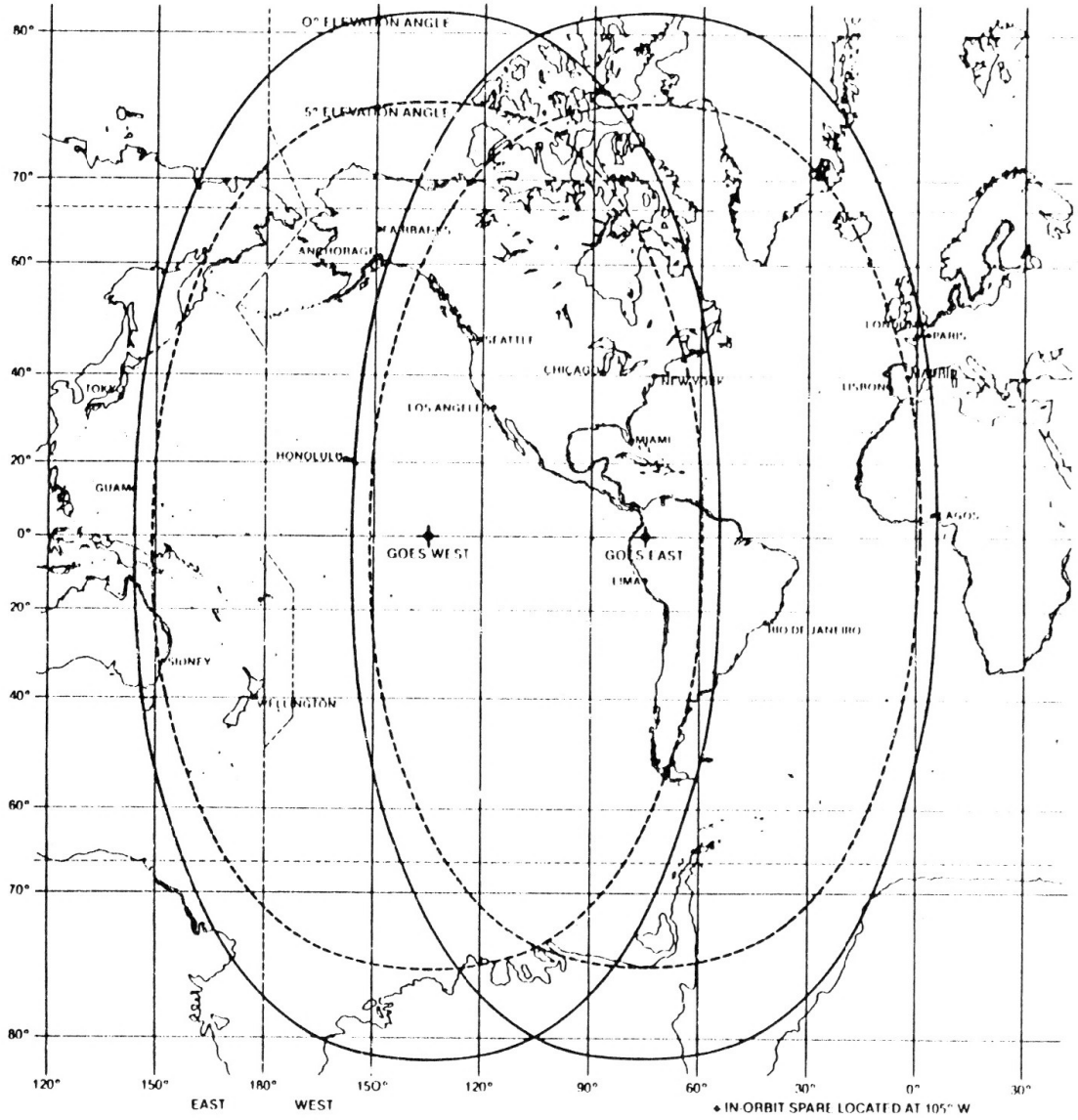
Three GOES satellites are in orbit, two operational and the third is in space storage. The two operational satellites are located at 135 and 75 West Longitude and the spare is at 105 West Longitude.

Coverage of each satellite is shown in the following illustration. GOES West transmits on 468.8250 MHz, GOES East on 468.8375 MHz. The signal strength of -139 dBm (output from an isotropic antenna).

The System provides an accuracy of better than 1.5 milliseconds traceable to UTC.

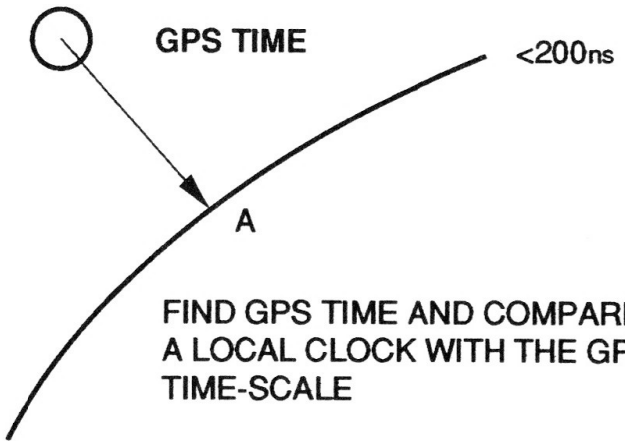
TIME TRANSFER VIA NIST GOES SATELLITES (CONT.)

Ball Efratom Division

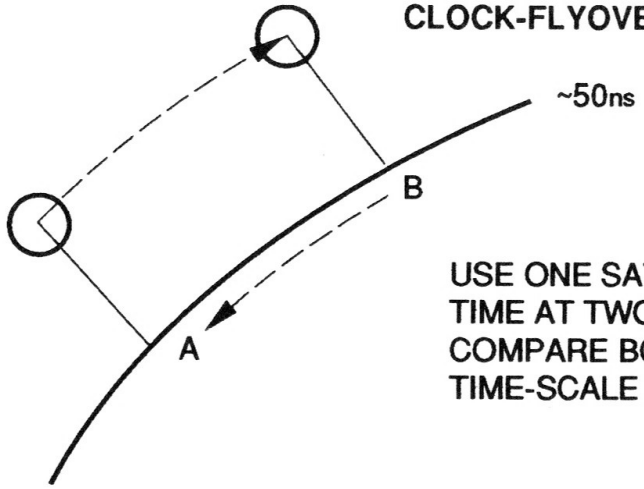


TIME & FREQUENCY TRANSFER VIA NAVSTAR-GPS SATELLITES

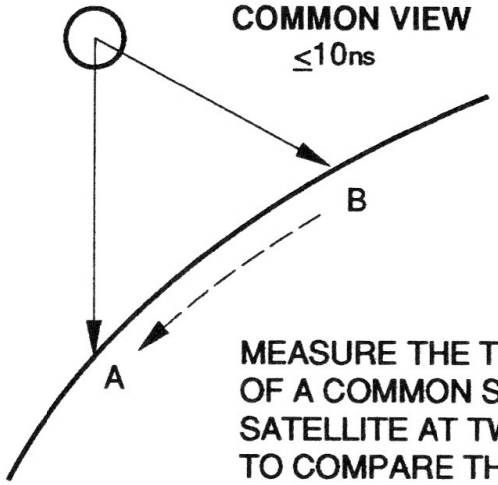
Ball Efratom Division



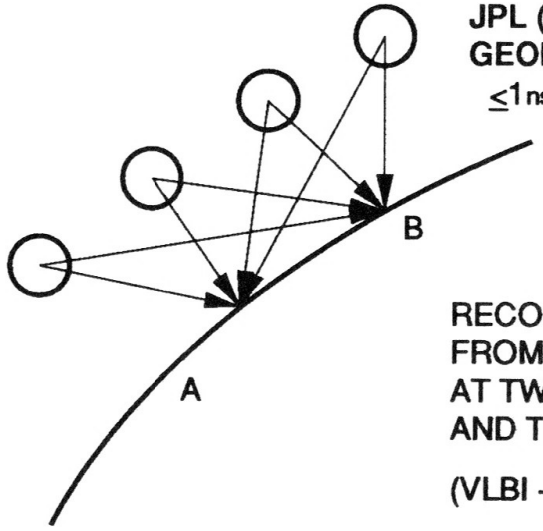
FIND GPS TIME AND COMPARE A LOCAL CLOCK WITH THE GPS TIME-SCALE



USE ONE SAT TO DECODE GPS TIME AT TWO LOCATIONS AND TIMES; COMPARE BOTH CLOCKS WITH GPS TIME-SCALE AND EACH OTHER



MEASURE THE TIME OF ARRIVAL OF A COMMON SIGNAL OF ONE SATELLITE AT TWO LOCATIONS TO COMPARE THE COMPUTED TIME OF TRANSMISSION ACCORDING TO THE TWO CLOCKS AND THUS COMPARE THE CLOCKS



RECORD SIGNALS FROM FOUR SATELLITES AT TWO LOCATIONS AND TIME DIFFERENCES

(VLBI - VERY LONG BASELINE INTERFEROMETRY)

COMMON-VIEW TIME & FREQUENCY TRANSFER CONCEPTS VIA GPS (1)

Ball Efratom Division

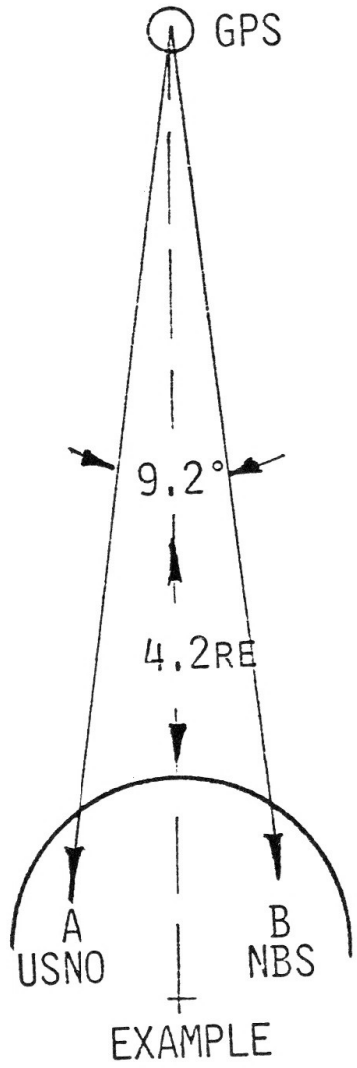
Basic Common View

- If two clocks at known coordinates A & B are in common-view of one GPS SAT, RCVR's at these two clock sites may coincidentally receive GPS clock time
-Subtract received times of arrivals as measured by clocks A & B
- Compensate for prop. errors
- Determine time between A & B

Capability (with error sources in hand)

~1 ηs time stability; < 10 ηs time accuracy
at distances of a few 1000 km

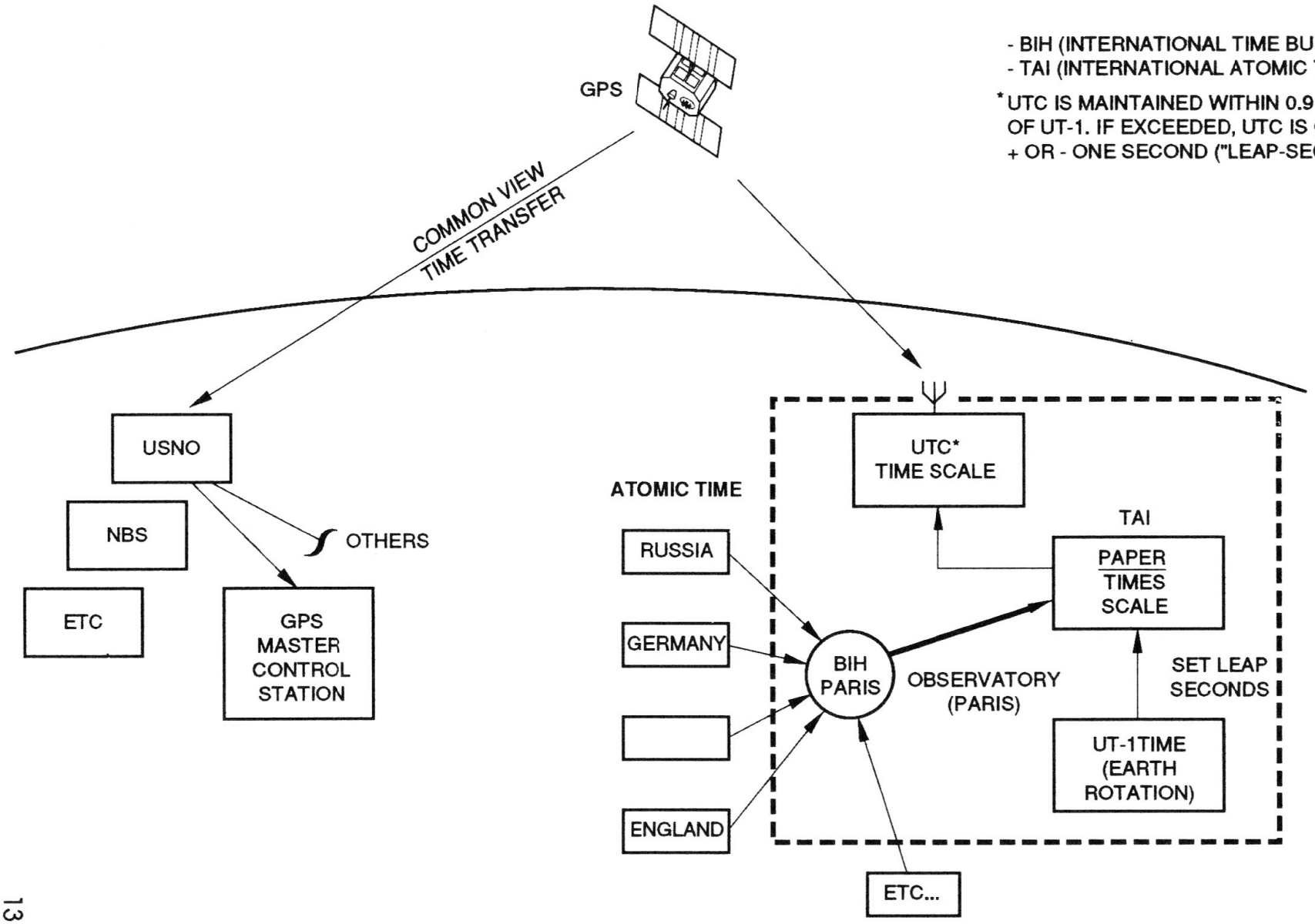
Error Sources -Ephemeris
-Ionospheric Delay
-Tropospheric Delays
-RCVR Group Delays
} All within a few nanoseconds RSS



(1) Proc. 34th Annual Freq. Cont. Symp. USA ERADCOM, Ft. Monmouth, N.J. 07703, May 1980 Accurate time and freq. transfer during common view of a GPS satellite. David W. Allan, Marc A. Weiss, NBS, Boulder, CO.

UTC (UNIVERSAL COORDINATED TIME) TRANSFERRED VIA GPS

Ball Efratom Division

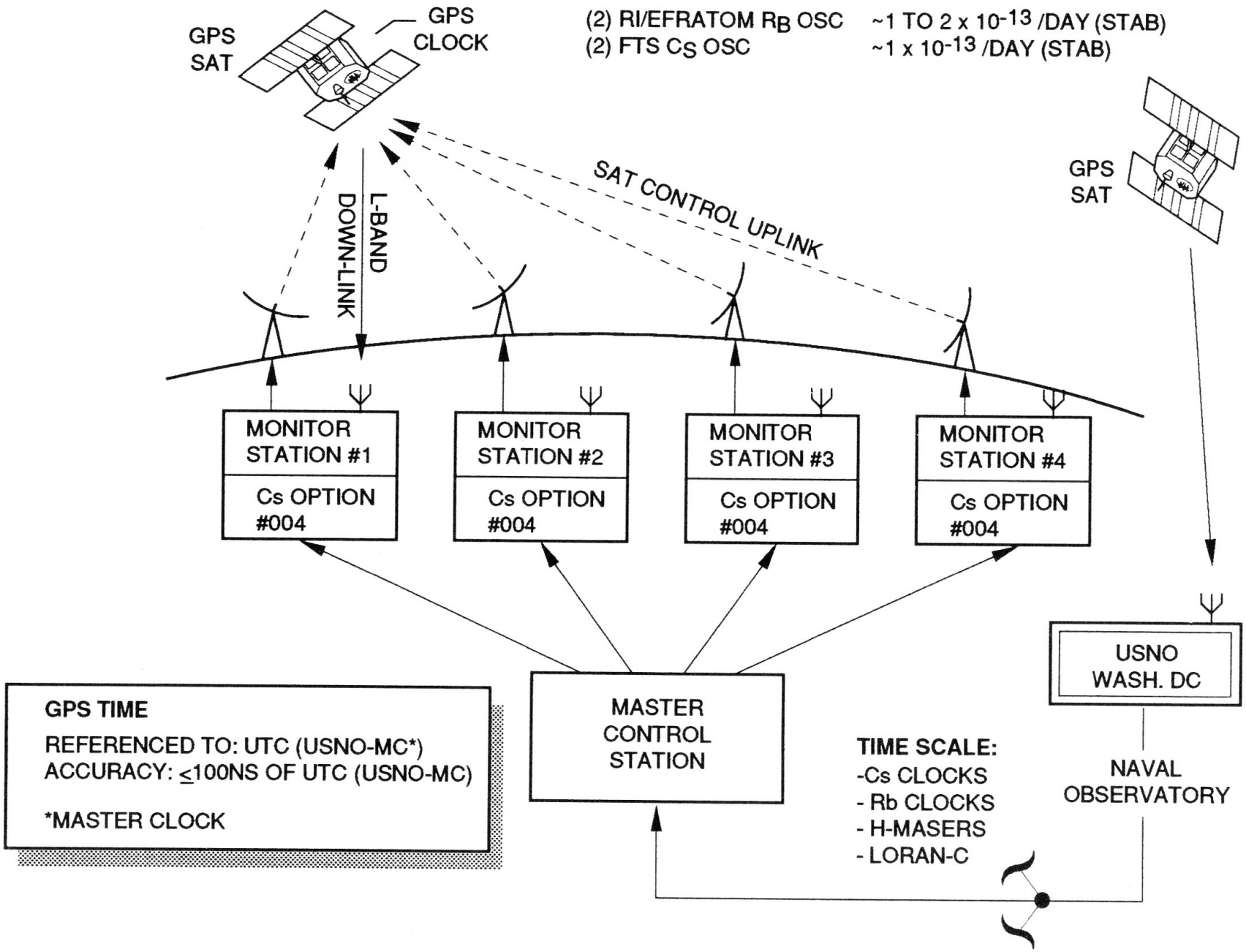


- BIH (INTERNATIONAL TIME BUREAU)
- TAI (INTERNATIONAL ATOMIC TIME)

*UTC IS MAINTAINED WITHIN 0.9 SEC. OF UT-1. IF EXCEEDED, UTC IS CORRECTED + OR - ONE SECOND ("LEAP-SECOND")

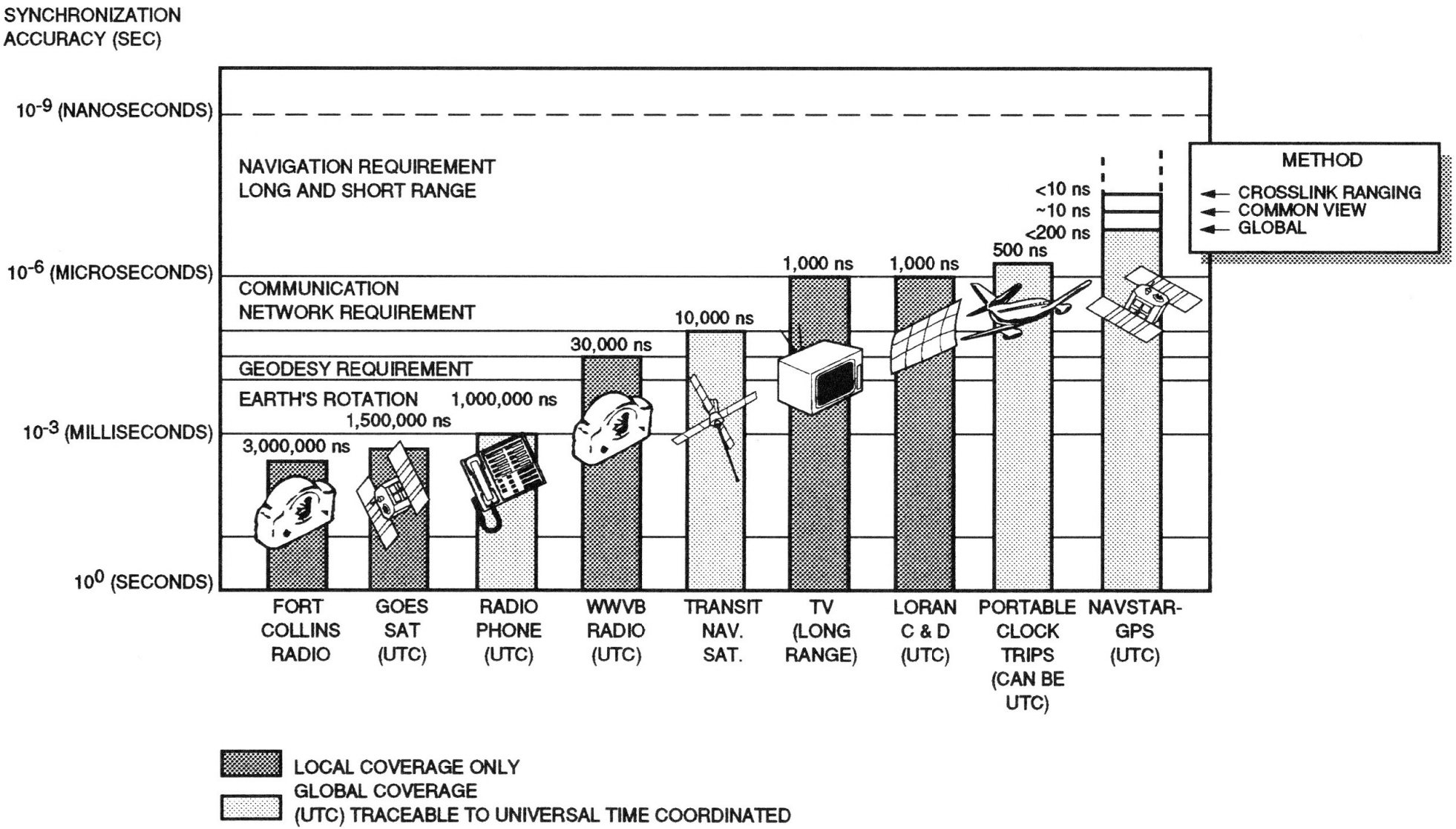
NAVSTAR-GPS TIME DEFINITION/QUALITY

Ball Efratom Division



SYNCHRONIZATION CAPABILITIES FROM VARIOUS SYSTEMS

Ball Efratom Division

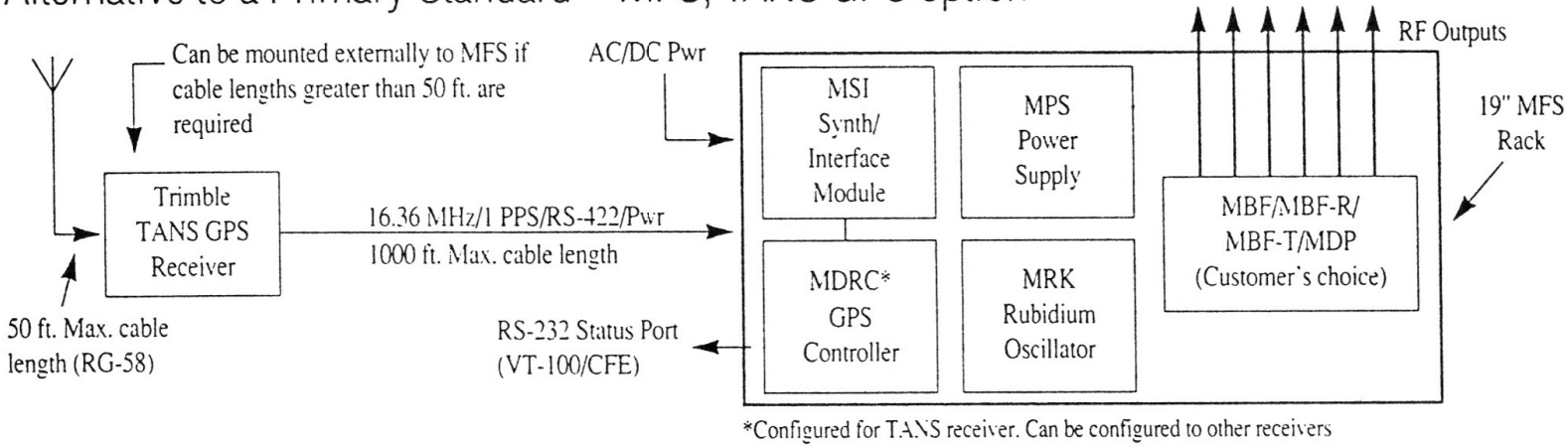


Courtesy of Tom Logsdon, Rockwell Int'l

EFRATOM MDRC TIME/FREQUENCY MODULAR SYSTEMS

Ball Efratom Division

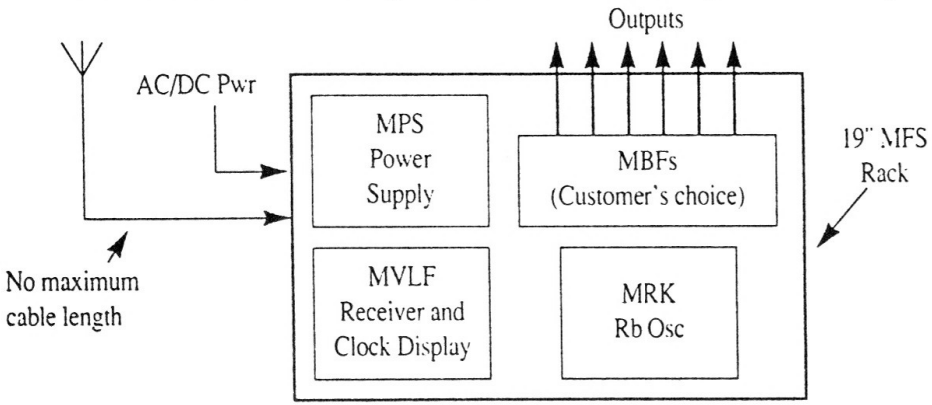
Alternative to a Primary Standard – MFS, TANS GPS option



*Configured for TANS receiver. Can be configured to other receivers

≤ 5E-12 Frequency Accuracy, ≤ 150 ns UTC Time Error (Selective availability disabled for at least one satellite)

Alternative to a Primary Standard – MFS, VLF/LF option



The MVLF uses nationally controlled/traceable low frequency transmitters (WWVB, MSF, DCF77, etc.) or the international Omega system to steer a Rb oscillator, providing an alternative to the GPS based system. (See MVLF module for details.)

1E-11 Frequency Accuracy, <1 μs UTC* Time Error with OMEGA

*UTC must first be set in MVLF

WHY DISCIPLINE A Rb OSCILLATOR?

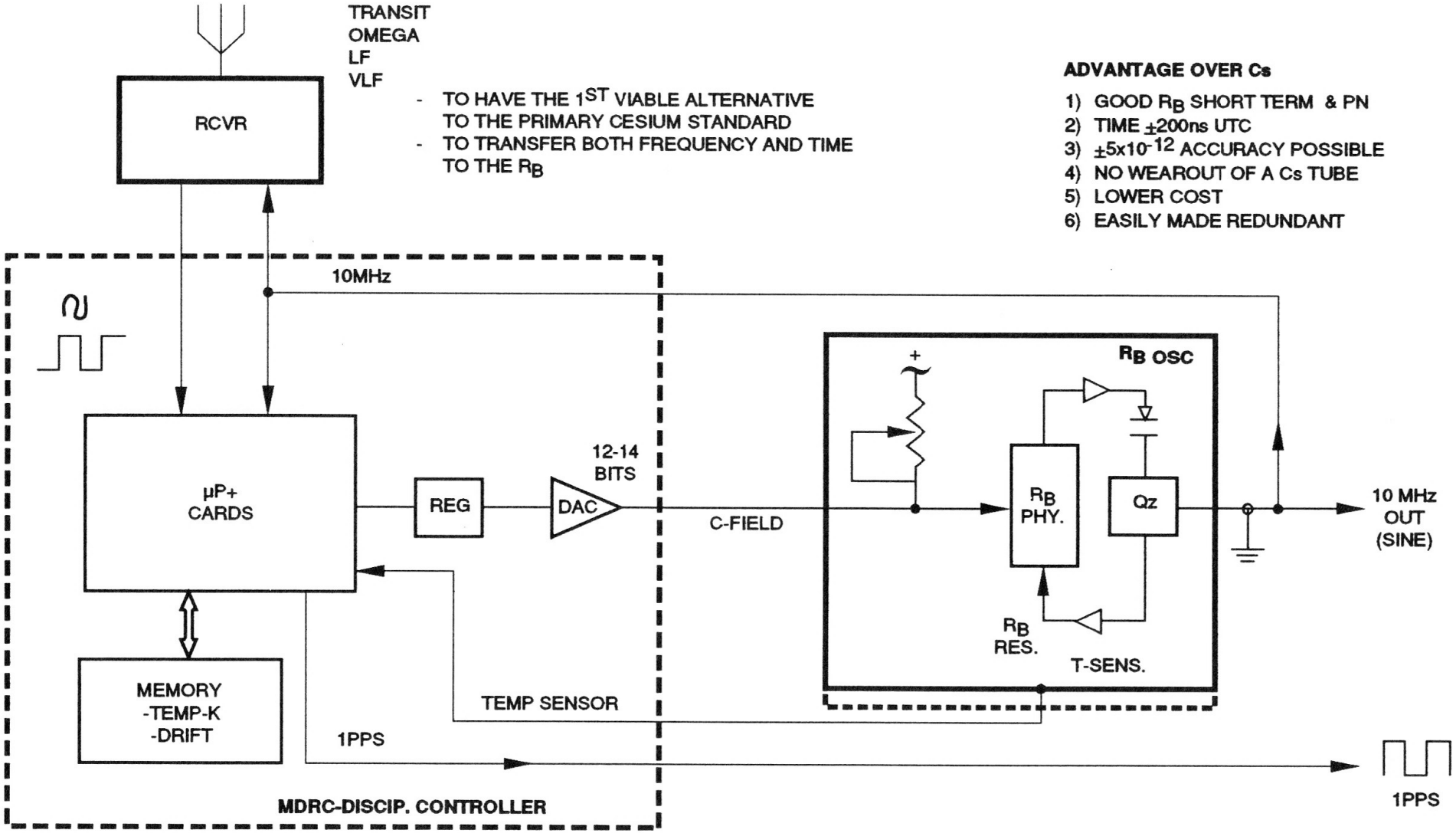
Ball Efratom Division

GPS
LORAN-C
TRANSIT
OMEGA
LF
VLF

- TO HAVE THE 1ST VIABLE ALTERNATIVE TO THE PRIMARY CESIUM STANDARD
- TO TRANSFER BOTH FREQUENCY AND TIME TO THE R_B

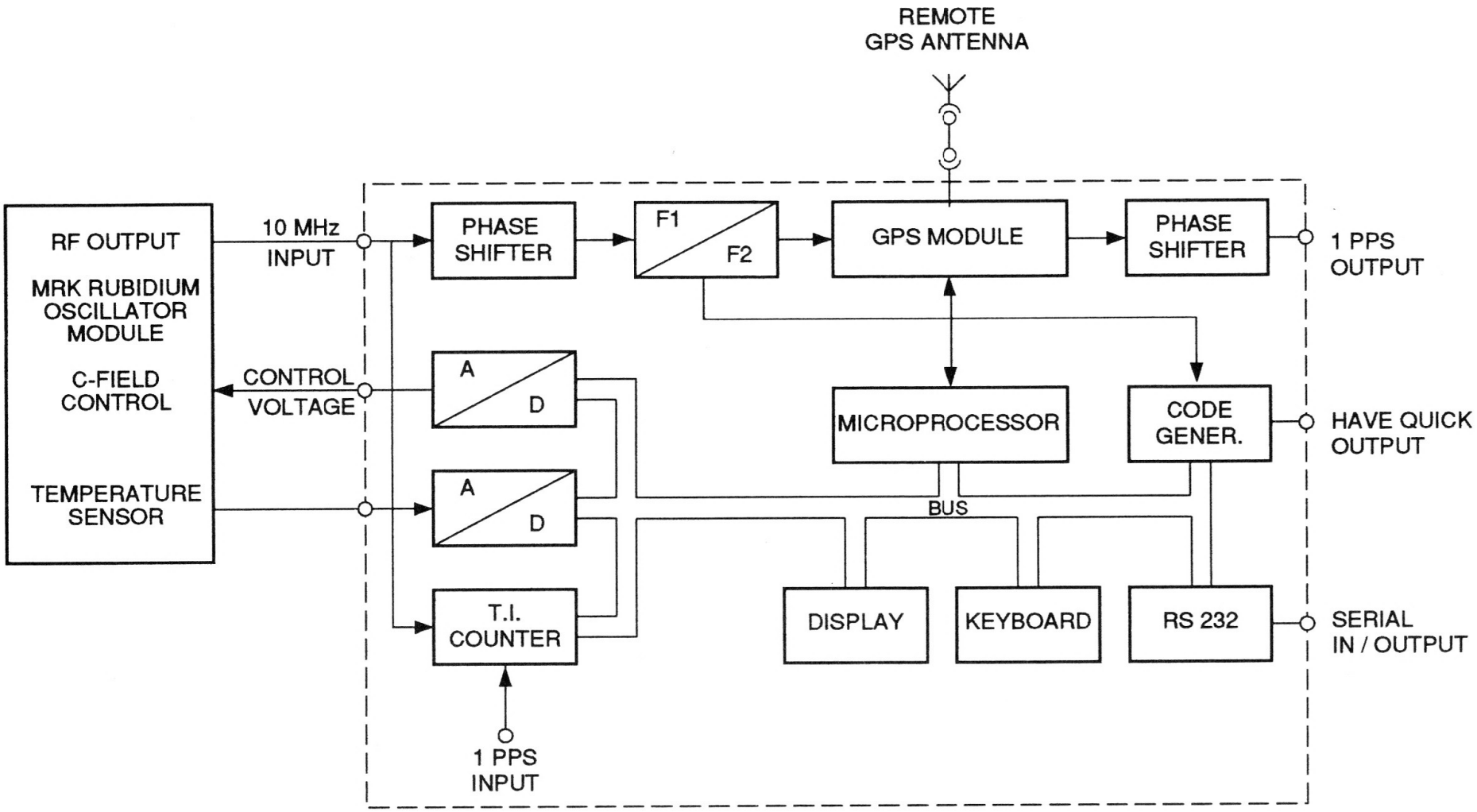
ADVANTAGE OVER Cs

1) GOOD R_B SHORT TERM & PN
2) TIME ±200ns UTC
3) $\pm 5 \times 10^{-12}$ ACCURACY POSSIBLE
4) NO WEAROUT OF A Cs TUBE
5) LOWER COST
6) EASILY MADE REDUNDANT



BLOCK DIAGRAM OF EFRATOM MDRC, GPS DISCIPLINED Rb T/F SYSTEM

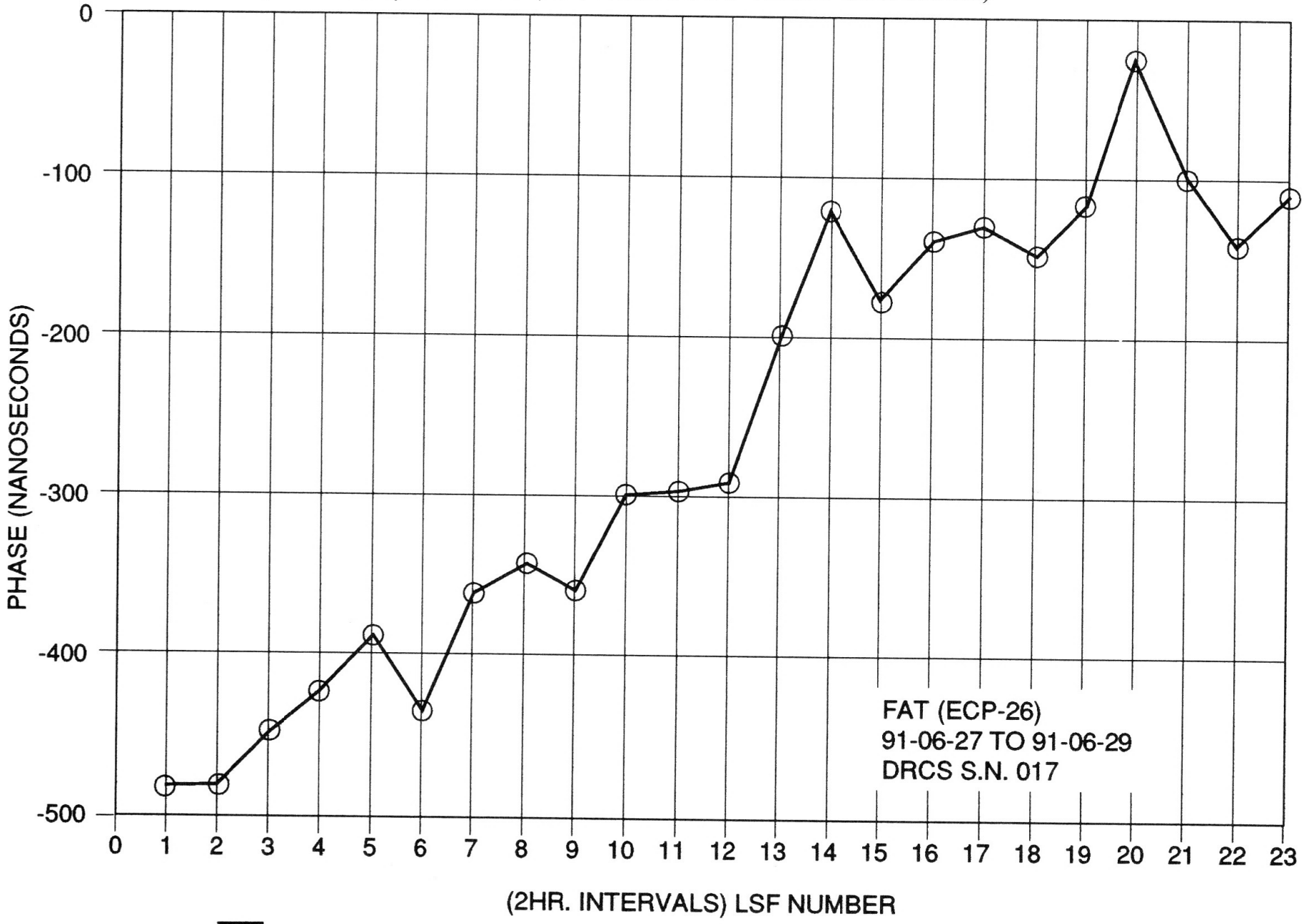
Ball Efratom Division



TYPICAL MDRC PERFORMANCE WITH FULL GPS COVERAGE

Ball Efratom Division

(WITH ±1 μs DITHER, CONTINUOUS VALID GPS DATA)

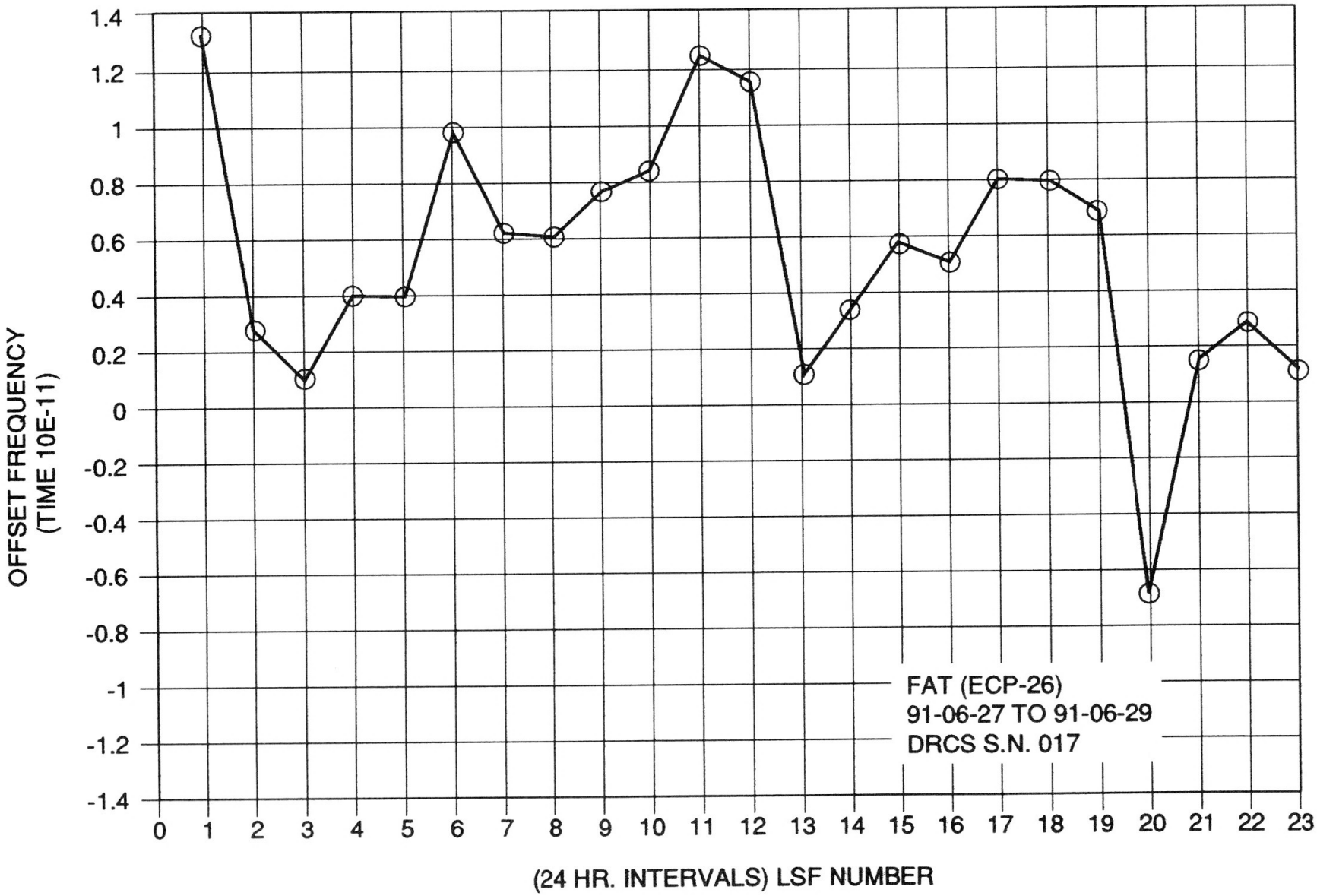


13.23

TYPICAL MDRC PERFORMANCE WITH FULL GPS COVERAGE

Ball Efratom Division

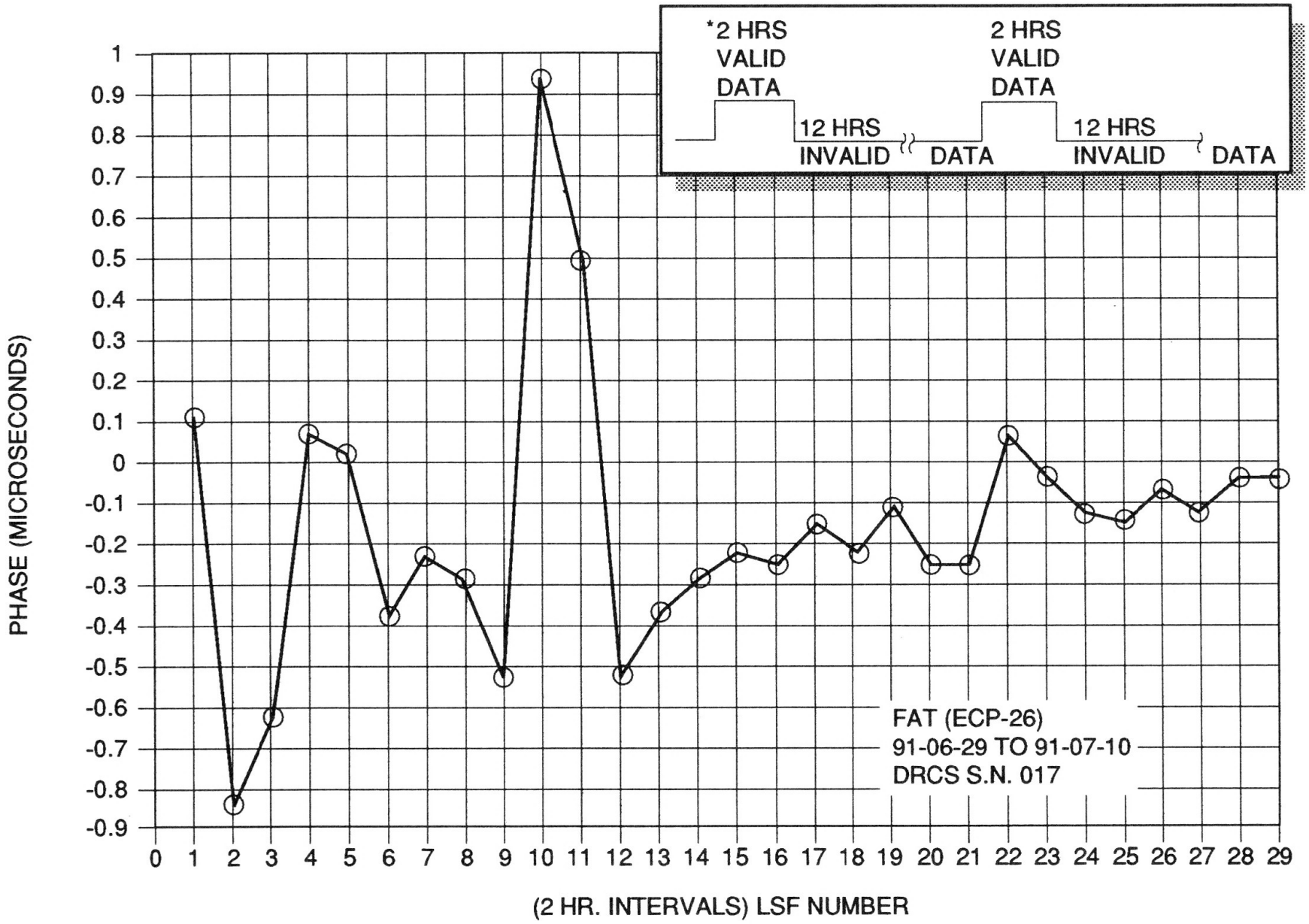
(WITH ±μs DITHER, CONTINUOUS VALID GPS DATA)



TYPICAL MDRC PERFORMANCE WITH DEGRADED GPS COV.

Efratom Division

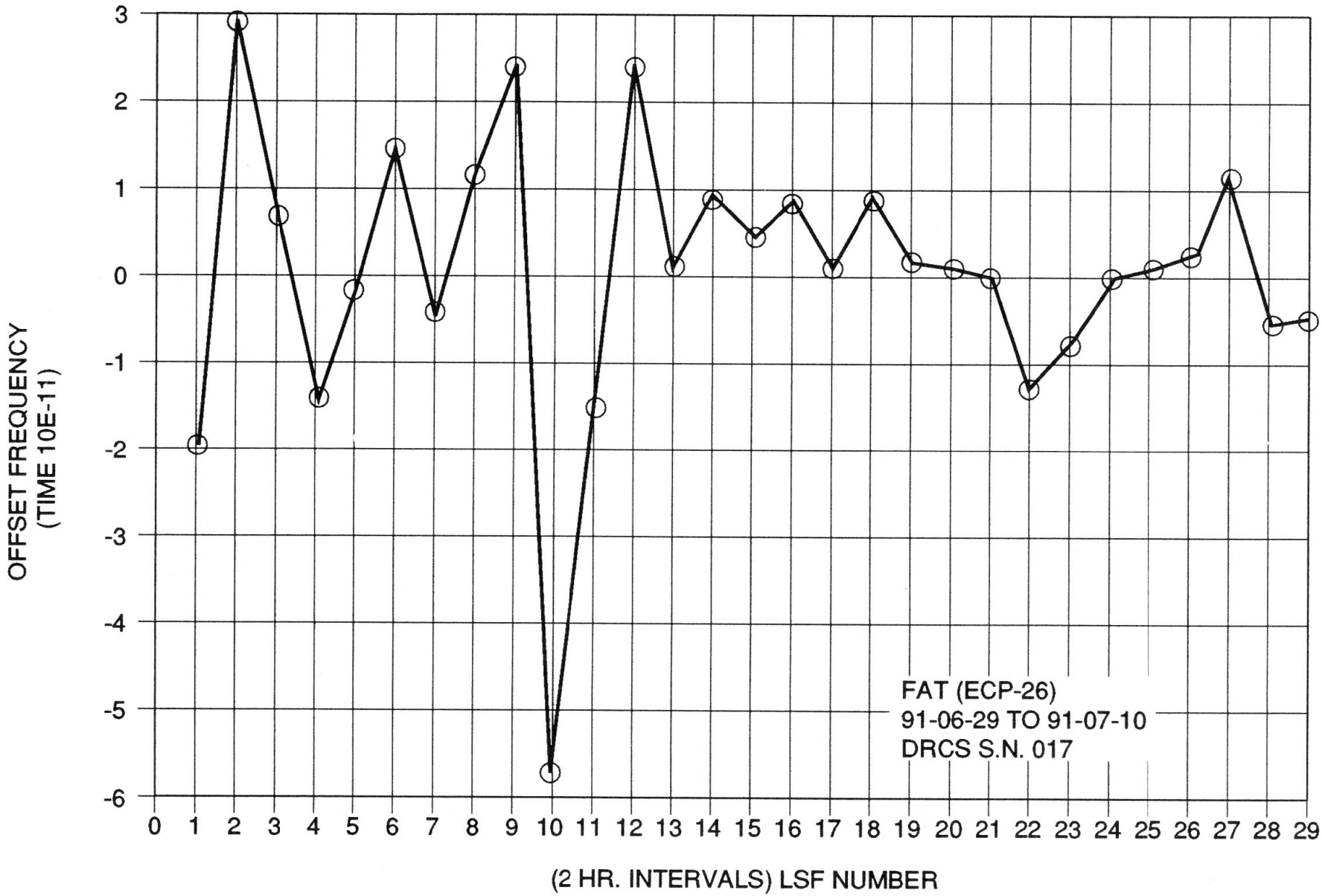
(WITH ±1 μs DITHER, INTERRUPTED VALID GPS DATA)



DRC PERFORMANCE WITH DEGRADED GPS COV.

(WITH ± μs DITHER, INTERRUPTED GPS SIGNAL)

Ball Efratom Division

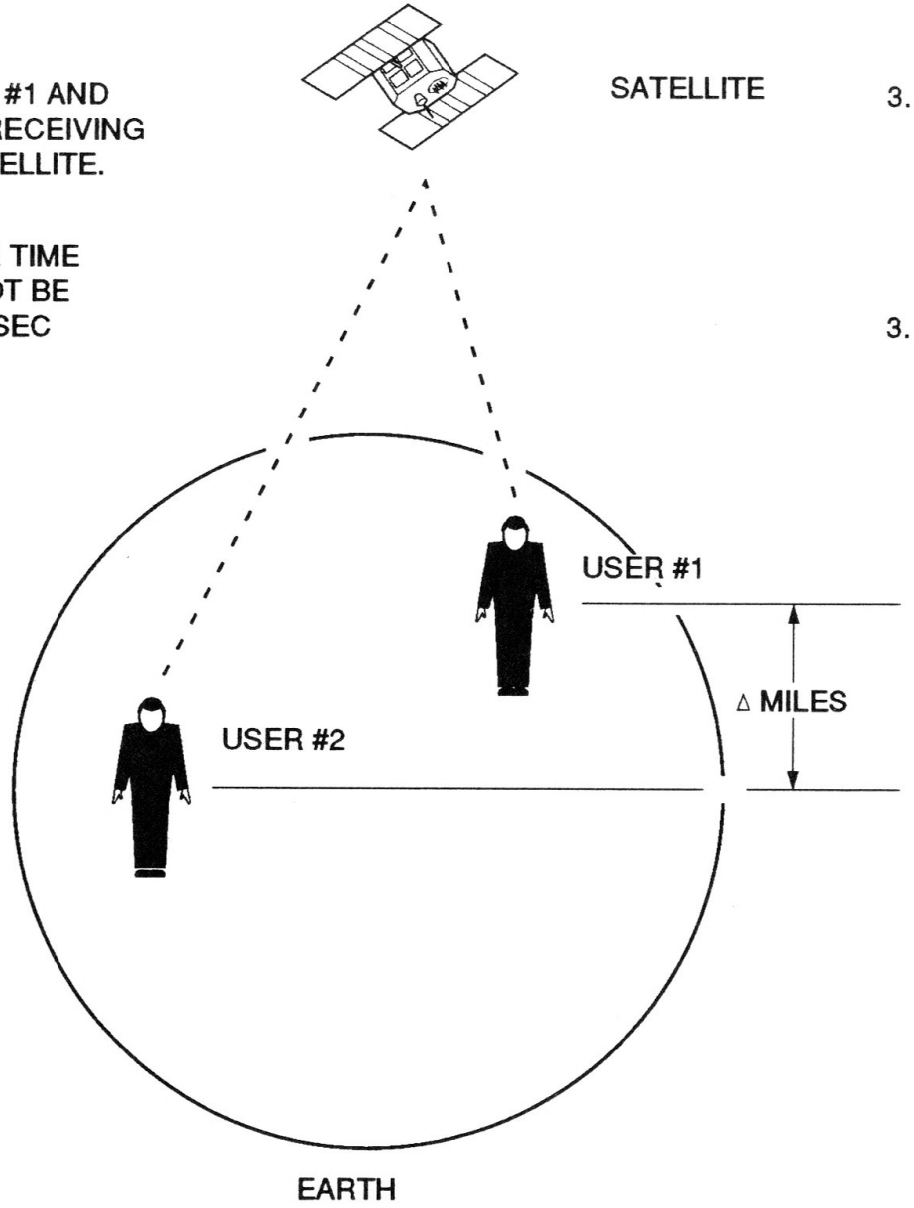


POSITIONING DATA IS NEEDED TO OBTAIN ACCURATE UTC

Ball Efratom Division

1. ASSUME USER #1 AND USER #2 ARE RECEIVING THE SAME SATELLITE.

2. BOTH RECEIVE TIME BUT IT WILL NOT BE TO <100 NANOSEC OF UTC.



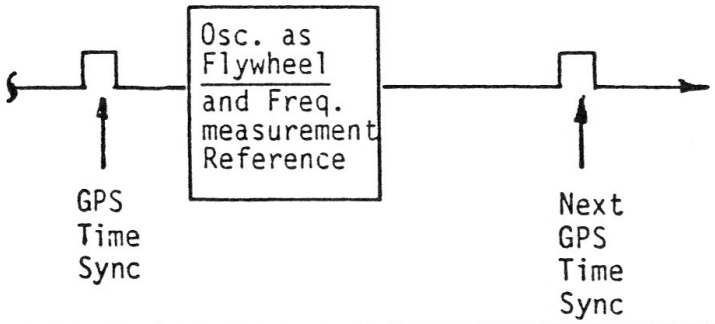
3. IF SIGNAL HAS TIME TO TRAVEL, FOR EXAMPLE, 1000 MILES FURTHER TO REACH USER #2 THEN PROPAGATION DELAY MUST BE CALIBRATED OUT.

3. USER MUST FIRST RESOLVE HIS POSITION BEFORE <100 NANOSEC OF UTC (USNO-MC) IS POSSIBLE.

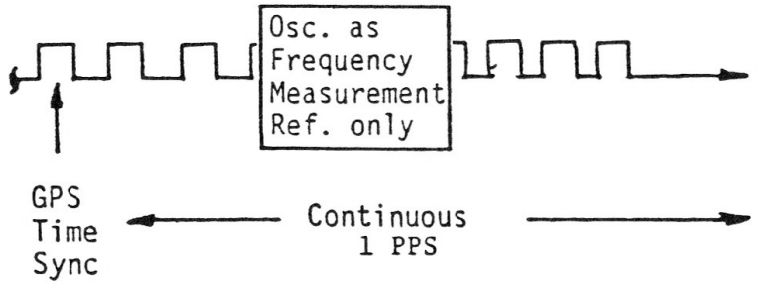
GPS RCVR & OSC ATTRIBUTES

Ball Efratom Division

Not a full constellation for 3D/ 24 hr. coverage, worldwide



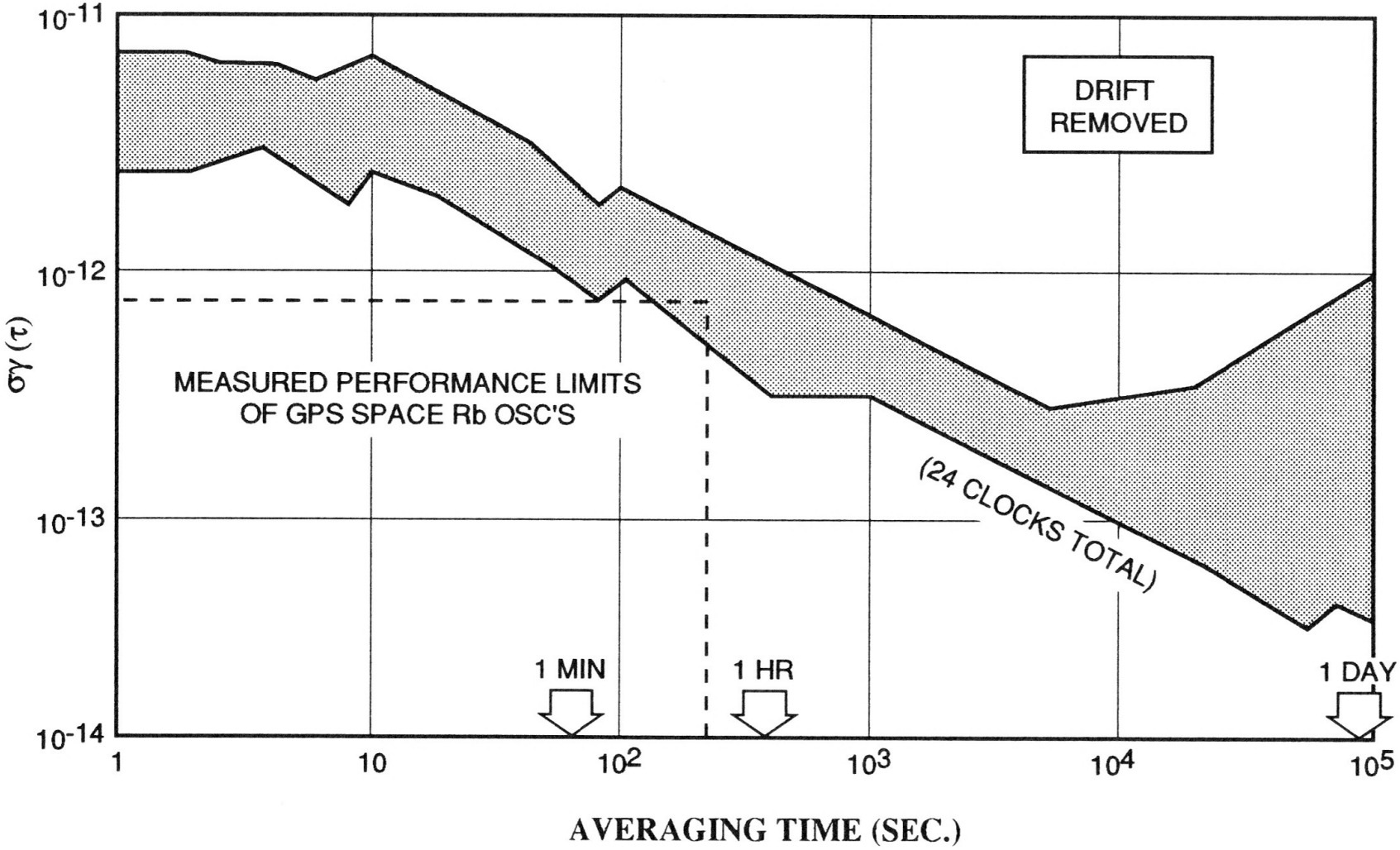
Full constellation for 3D/ 24 hr. coverage, worldwide



	DESIRED ATTRIBUTES [1]	USING GPS RCVR FOR TIME SYNC [2]	USER OSCILLATOR [3]	USING GPS RCVR FOR TIME SYNC [4]	USER OSCILLATOR [5]
(a)	ACCURATE TIME	GIVES ACCURATE TIME (<100ns)	MAINTAINS TIME BETWEEN SYNC'S (Rb 10 to 100ns, Qz 1 to 10μs	GIVES ACCURATE TIME (<100ns)	NO LONGER NEEDED FOR THIS FUNCTION
(b)	ACCURATE FREQUENCY	CAN CORRECT USER OSC. TO 10^{-12} to 10^{-13}/day (But NOT by GPS signal alone)	RESOLVES FREQ. ACCURACY AND MAINTAINS BETWEEN SYNC'S	CAN CORRECT USER OSC. TO 10^{-12} to 10^{-13}/day (But not by GPS signal alone)	STILL NEED OSC. FOR STAB. MEASUREMENT (10^3 TO 10^4 Sec.) SAMPLING TIME TO REALIZE A MEASUREMENT AT 1x10-12 TO p10^{13}
(c)	SHORT TERM FREQUENCY STABILITY	NO HELP	IS SOURCE OF SHORT TERM STABILITY	NO HELP	IS SOURCE OF SHORT TERM STABILITY
(d)	PHASE NOISE	NO HELP	IS SOURCE OF PHASE NOISE SPEC	NO HELP	IS SOURCE OF PHASE NOISE SPEC

NAVSTAR-GPS SATELLITE CLOCK STABILITY PERFORMANCE

Ball Efratom Division



Courtesy of Tom Logsdon, Rockwell Int'l

NAVIGATION AND THE OSCILLATOR

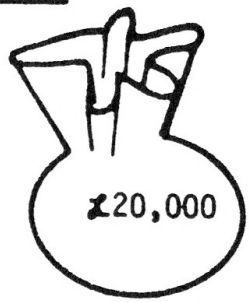
- Historical Development of Clocks
- The Basic Concept of One-Way Ranging
- Atomic Oscillator Applications

Note: Some charts and portions of others taken from briefings given by Rockwell Int'l, Space Operations & Satellite Systems Division. (Used by permission T. Logsdon, C. Helms)

HISTORICAL PERSPECTIVE

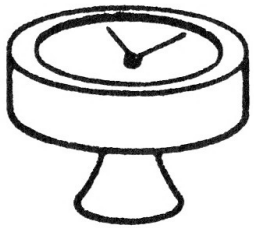
Ball Efratom Division

1714



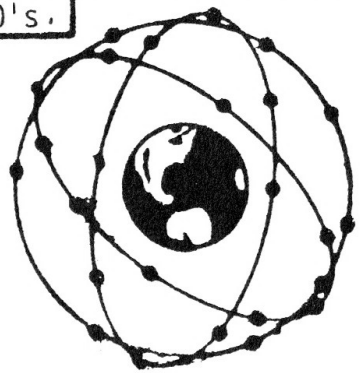
BRITISH BOARD OF LONGITUDE OFFERED £20,000 FOR A NAVIGATION ACCURACY OF 30 N.MI. (AFTER 6 WEEKS AT SEA)

1761



JOHN HARRISON WON WITH A CHRONOMETER THAT LOST ONLY 1 SECOND PER DAY

1980's.



GPS SYSTEM UNDER CONSTRUCTION WILL NAVIGATE WITHIN 30 FEET WITH CLOCKS THAT WILL LOSE ONLY 1 SECOND EVERY 100,000 YEARS

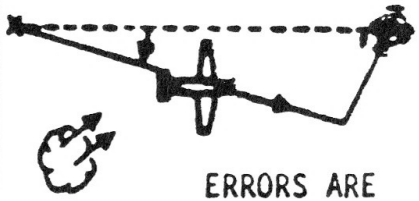
METHODS OF NAVIGATION

Ball Efratom Division

PILOTING*

FIXING POSITION RELATIVE TO RECOGNIZABLE OBJECTS

DEAD RECKONING



EXTRAPOLATING POSITION FROM MEASURED VELOCITY INCREMENTS

ERRORS ARE CUMULATIVE

CELESTIAL NAVIGATION

COMPUTING POSITION FROM TIMED SIGHTINGS OF CELESTIAL BODIES

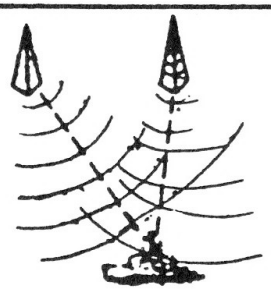
POSITION ERROR = 0.25 N MI/SEC

INERTIAL NAVIGATION

DETERMINING POSITION FROM GYROSCOPIC FORCES AND INTEGRATING ACCELEROMETERS

ERRORS ARE CUMULATIVE

ELECTRONIC NAVIGATION

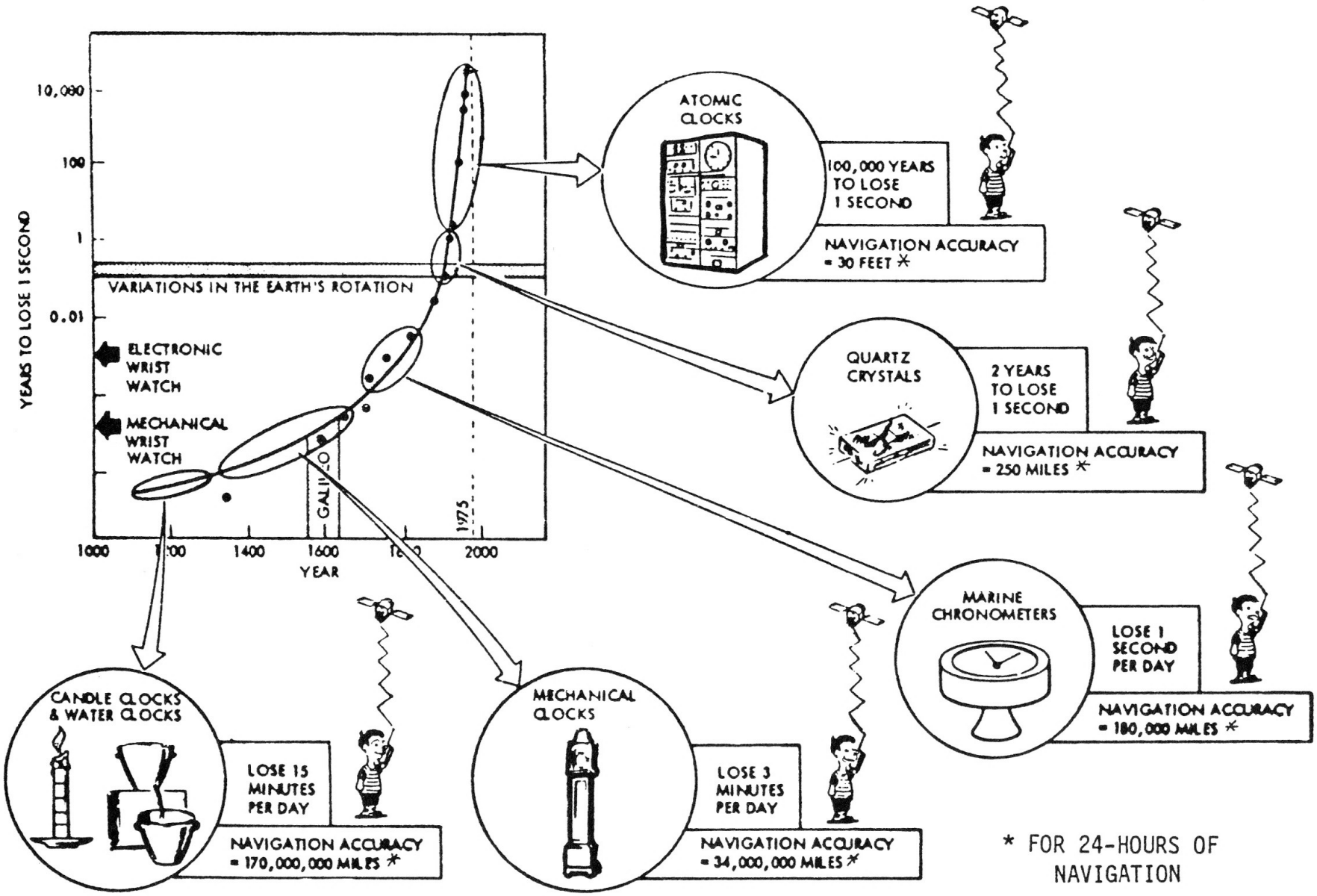


FINDING POSITION FROM RADIO WAVES SENT OUT BY MULTIPLE TRANSMITTERS

POSITION ERROR = $1FT/10^{-9}$ SECONDS

THE HISTORICAL DEVELOPMENT OF ACCURATE CLOCKS

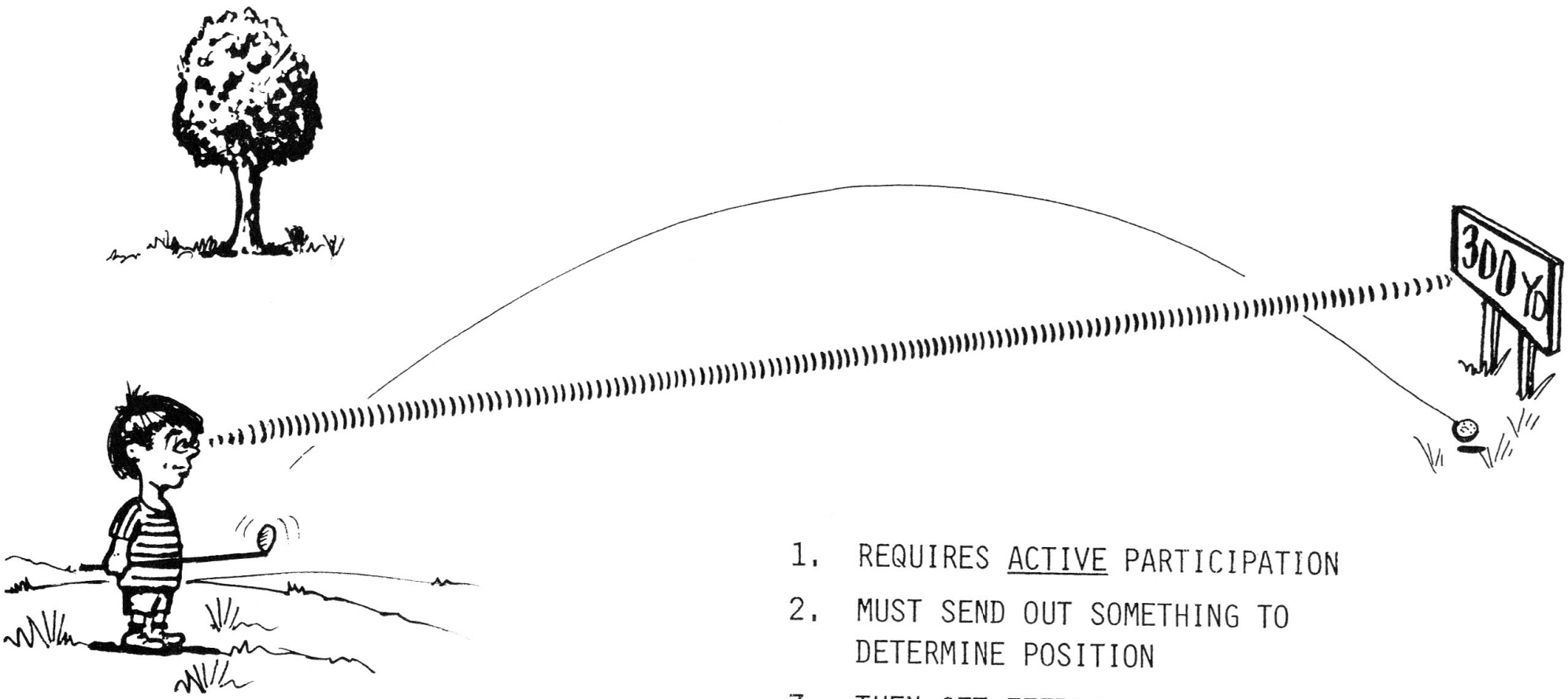
Ball Efratom Division



* FOR 24-HOURS OF NAVIGATION

COMMON 2-WAY RANGING SYSTEM

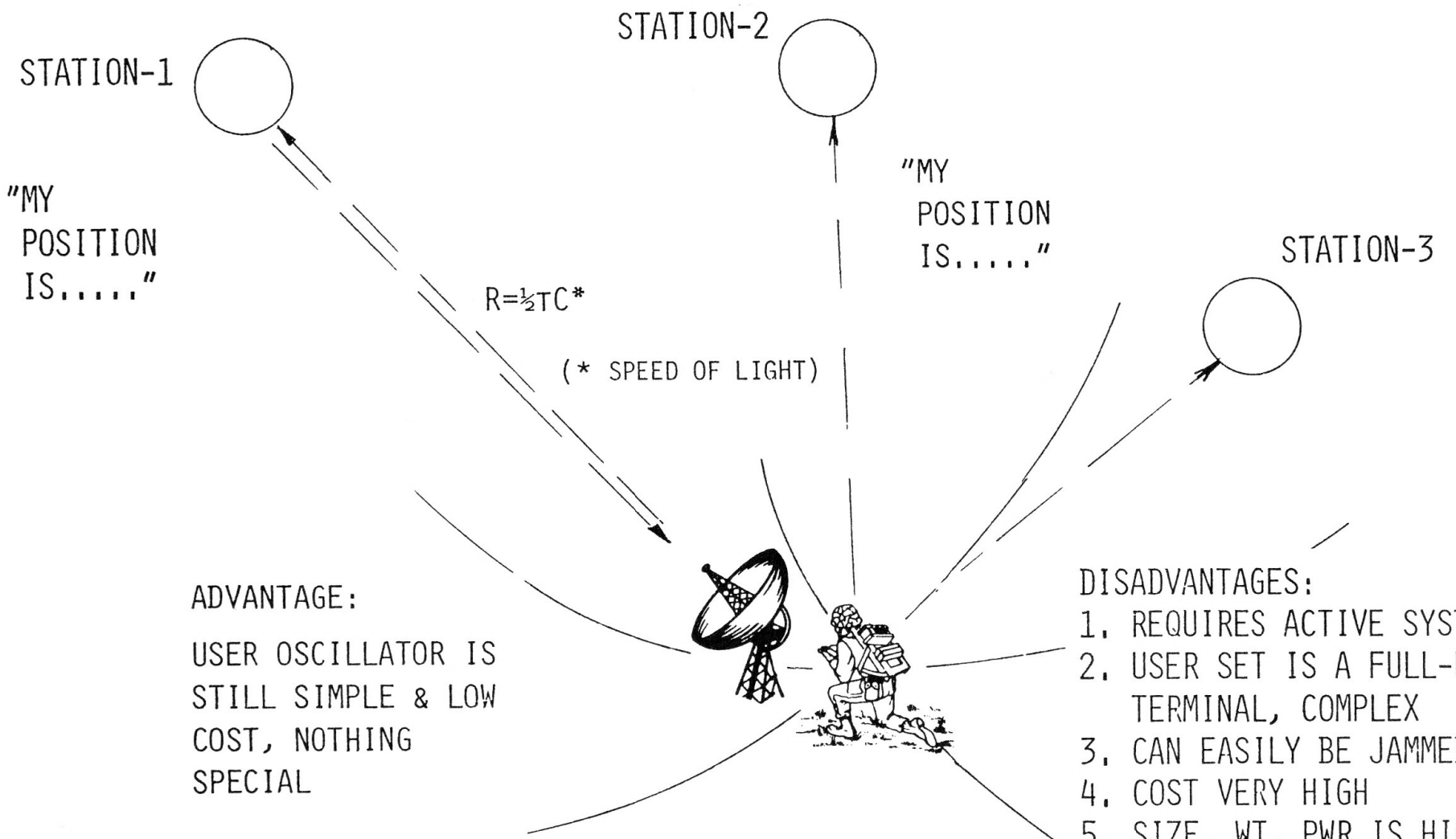
Ball Efratom Division



1. REQUIRES <u>ACTIVE</u> PARTICIPATION
2. MUST SEND OUT SOMETHING TO DETERMINE POSITION
3. THEN GET FEEDBACK ON RANGE

MORE COMPLEX 2-WAY RANGING SYSTEM

Ball Efratom Division



ADVANTAGE:

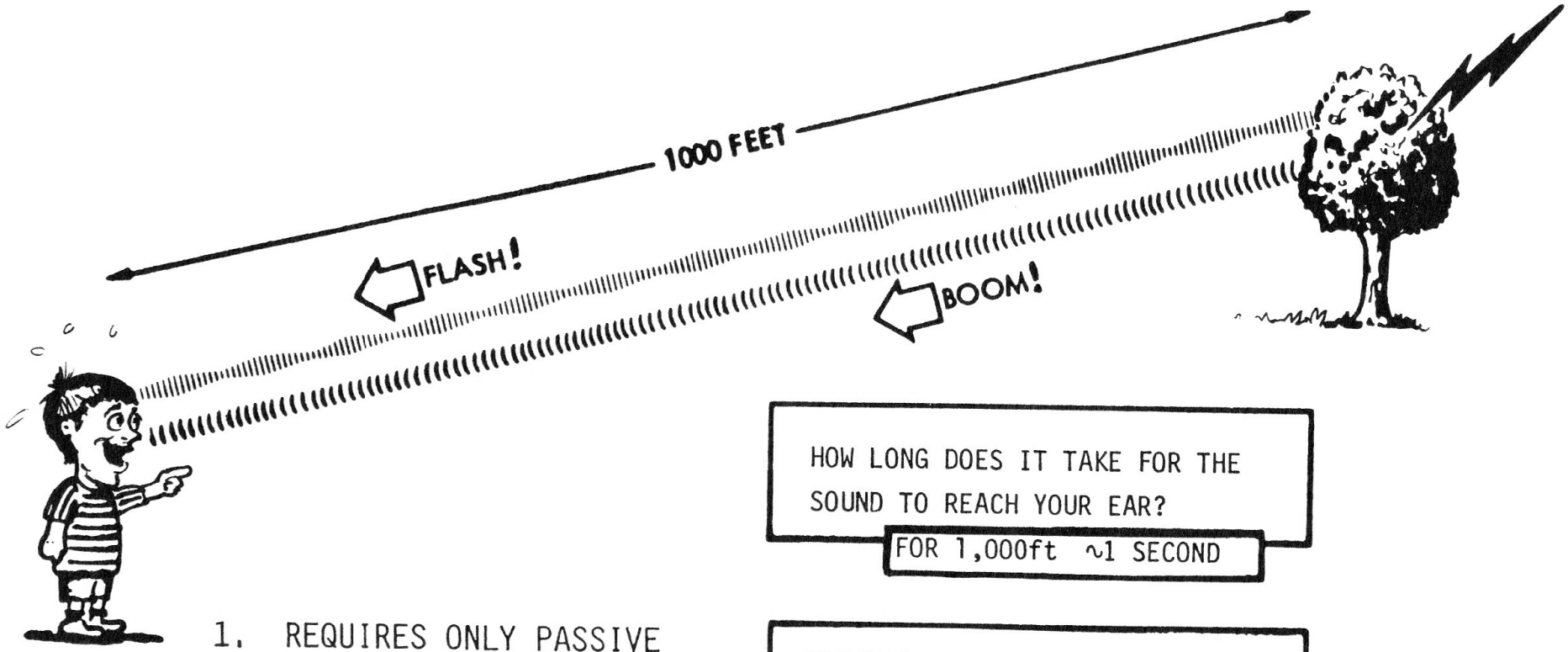
USER OSCILLATOR IS STILL SIMPLE & LOW COST, NOTHING SPECIAL

DISADVANTAGES:

1. REQUIRES ACTIVE SYSTEM
2. USER SET IS A FULL-UP TERMINAL, COMPLEX
3. CAN EASILY BE JAMMED
4. COST VERY HIGH
5. SIZE, WT, PWR IS HIGH
6. REQUIRES POINTING

COMMON 1-WAY RANGING SYSTEM

Ball Efratom Division



1. REQUIRES ONLY PASSIVE PARTICIPATION
2. NOTHING SENT OUT; RECEIVER OPS ONLY
3. EYE STARTS CLOCK
4. EAR STOPS IT

HOW LONG DOES IT TAKE FOR THE SOUND TO REACH YOUR EAR?

FOR 1,000ft ~1 SECOND

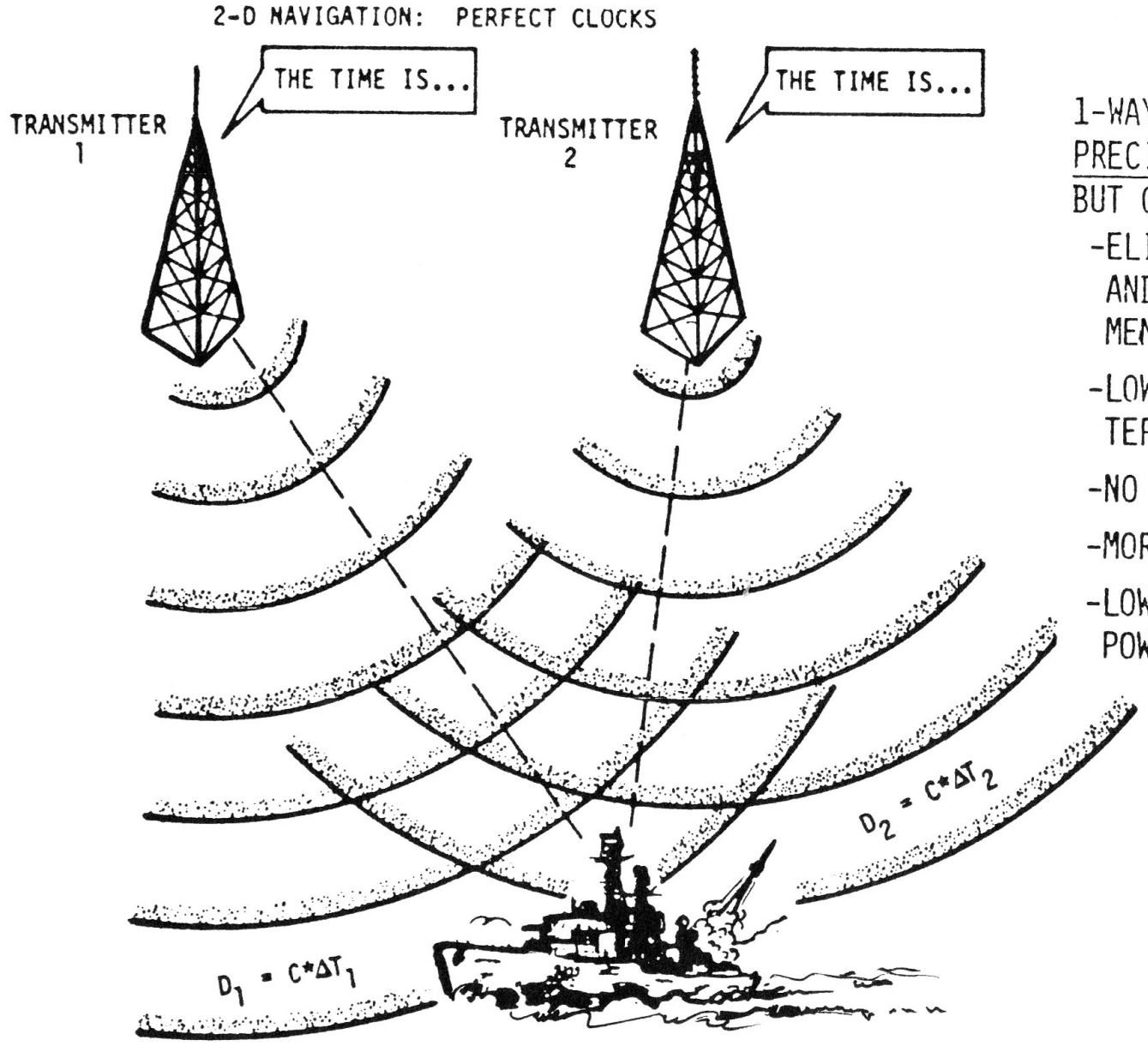
ELECTRONIC NAVIGATION OPERATES THE SAME WAY BUT LIGHT/RF IS USED INSTEAD OF SOUND.

HOW LONG DOES IT TAKE-THE LIGHT/RF TO REACH YOUR EYE?

1 MILLIONTH OF A SECOND FOR 1,000ft

ELECTRONIC 1-WAY RANGING SYSTEM

Ball Efratom Division

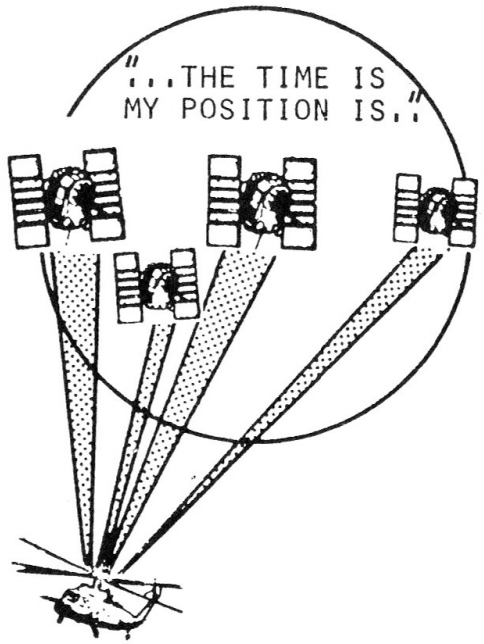


1-WAY SYSTEMS REQUIRE PRECISION OSCILLATORS, BUT OFFER:

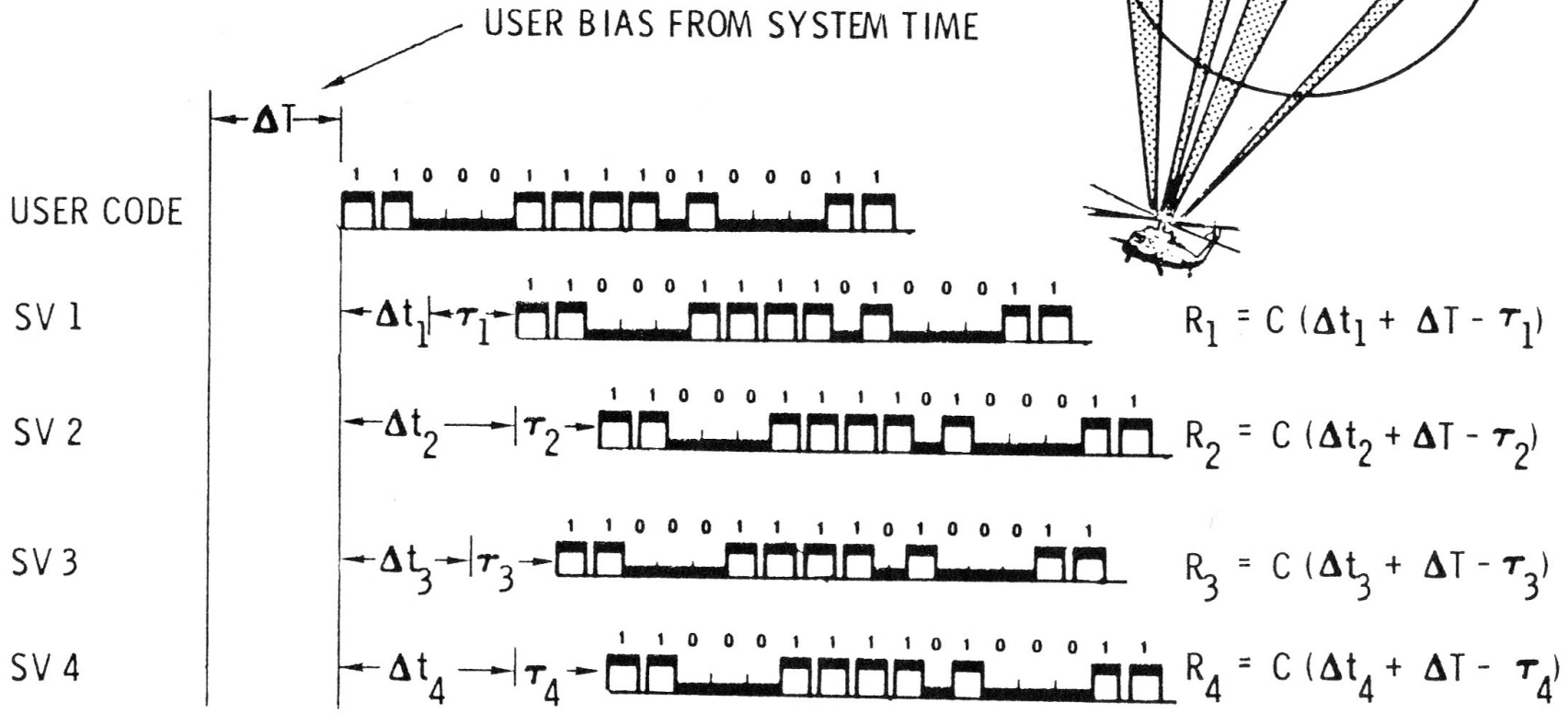
- -ELIMINATION OF SEND AND RECEIVE REQUIREMENT
- -LOWER COST USER TERMINAL
- -NO ANTENNA POINTING
- -MORE JAM-PROOF
- -LOWER SIZE, WT. AND POWER

SPACEBORNE 1-WAY RANGING

Ball Efratom Division



BIASED-CLOCKS , SATELLITE & USER
(THE REALISTIC NAVSTAR SYSTEM)

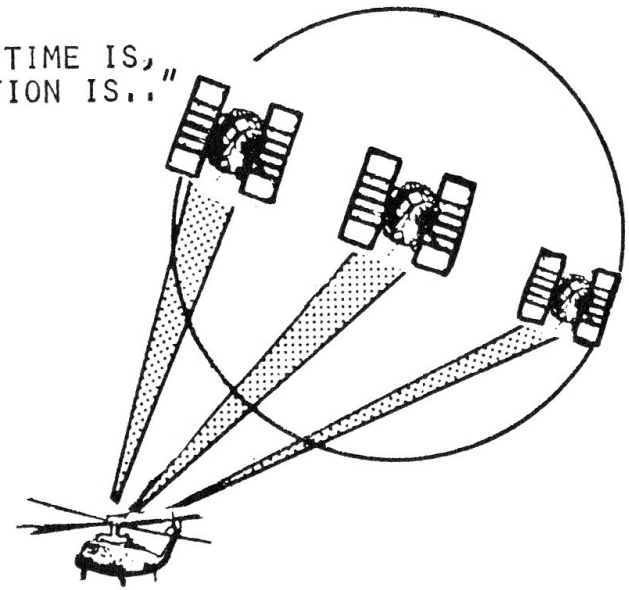


CLOCK DATA IN DOWNLINK MESSAGE CORRECTS FOR SV CLOCK BIASES (τ)

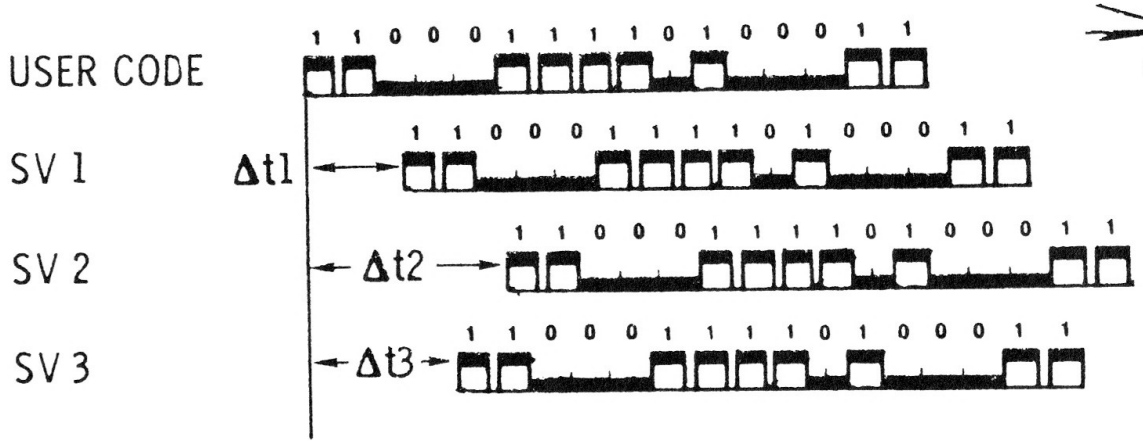
4 EQUATIONS - 4 UNKNOWNS

SPACEBORNE (CONTINUED)

Ball Efratom Division



PERFECT CLOCKS-SATELLITE AND USER
(ONLY 3-SATS NEEDED)

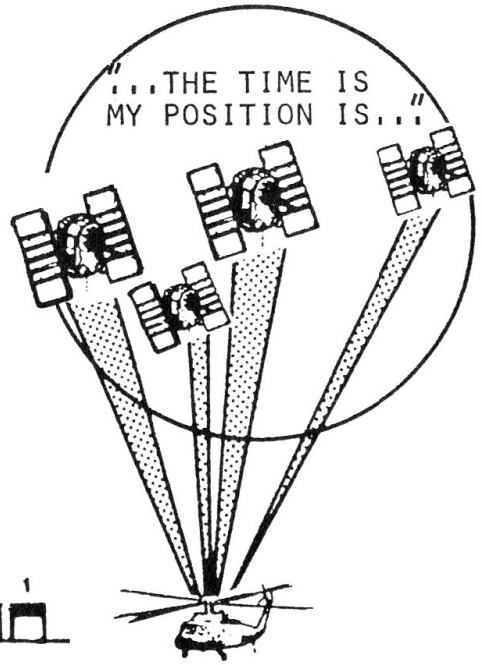


$R1 = C\,\Delta t1$

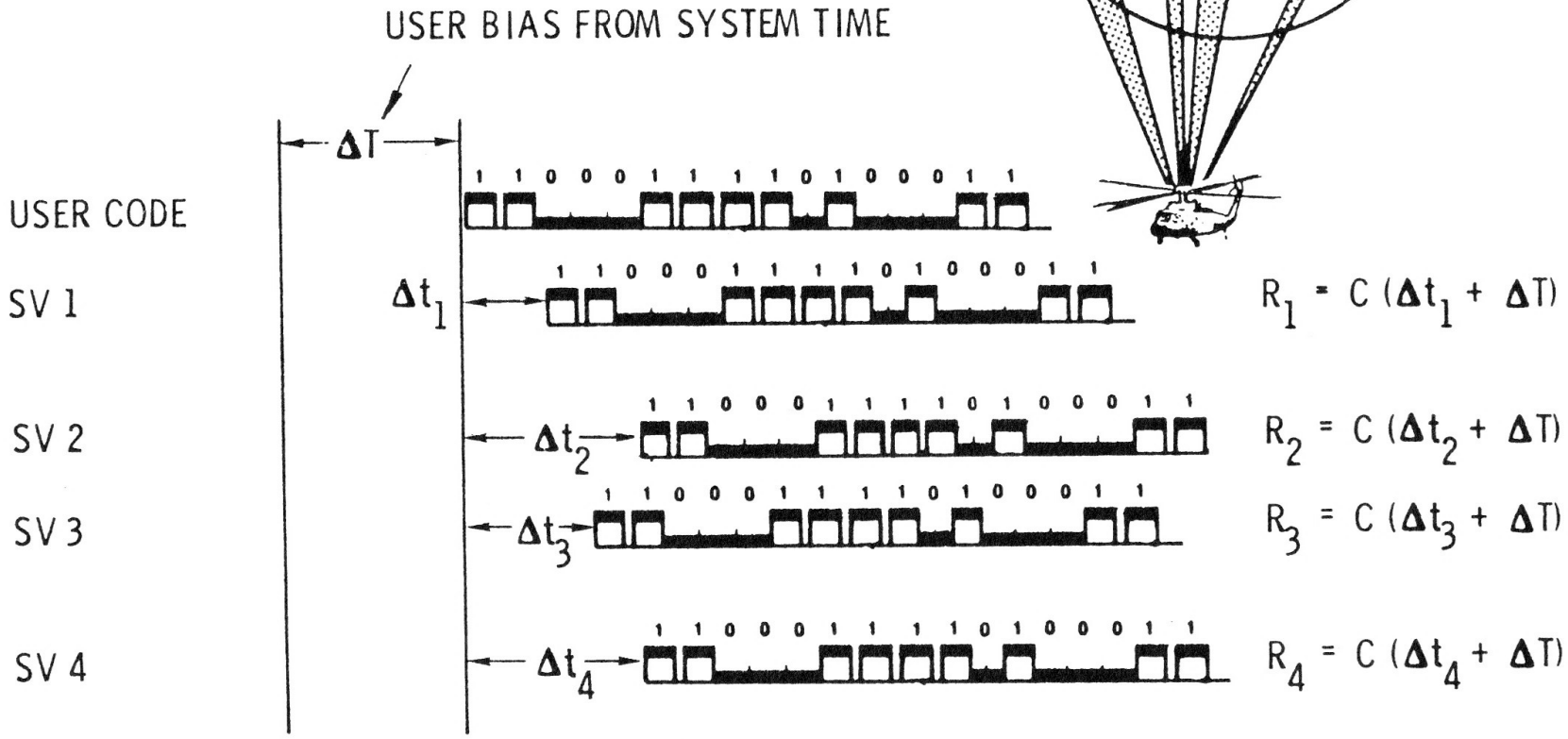
$R2 = C\,\Delta t2$

$R3 = C\,\Delta t3$

Ball Efratom Division



PERFECT-SATELLITE CLOCKS
BIASED USER CLOCK (NOW 4-SATS NEEDED)



4 EQUATIONS - 4 UNKNOWNS

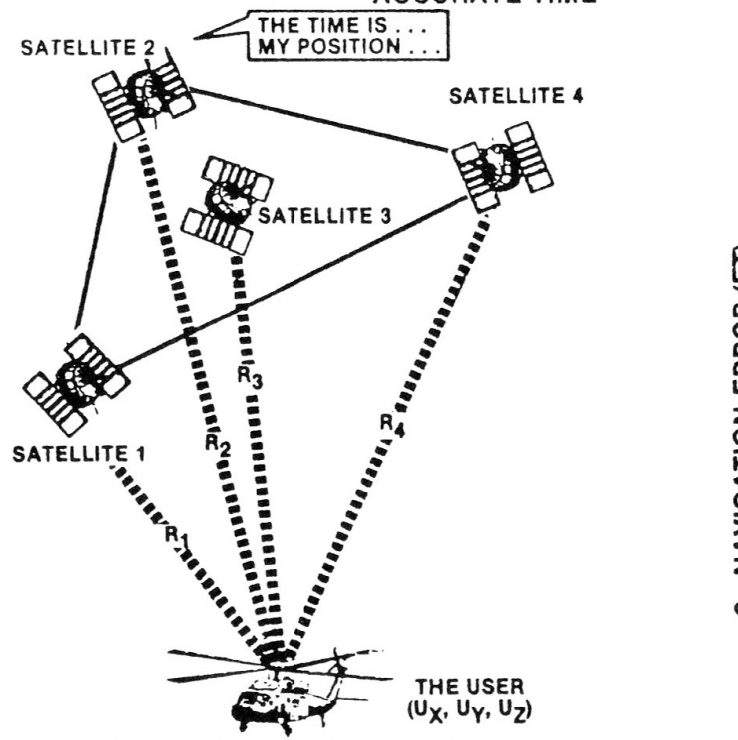
THE NAVSTAR GPS

Ball Efratom Division

DESCRIPTION

SPHERICAL RANGING:
- 3D POSITION
- 3D VELOCITY

(ANY COORDINATE SYSTEM)
- ACCURATE TIME

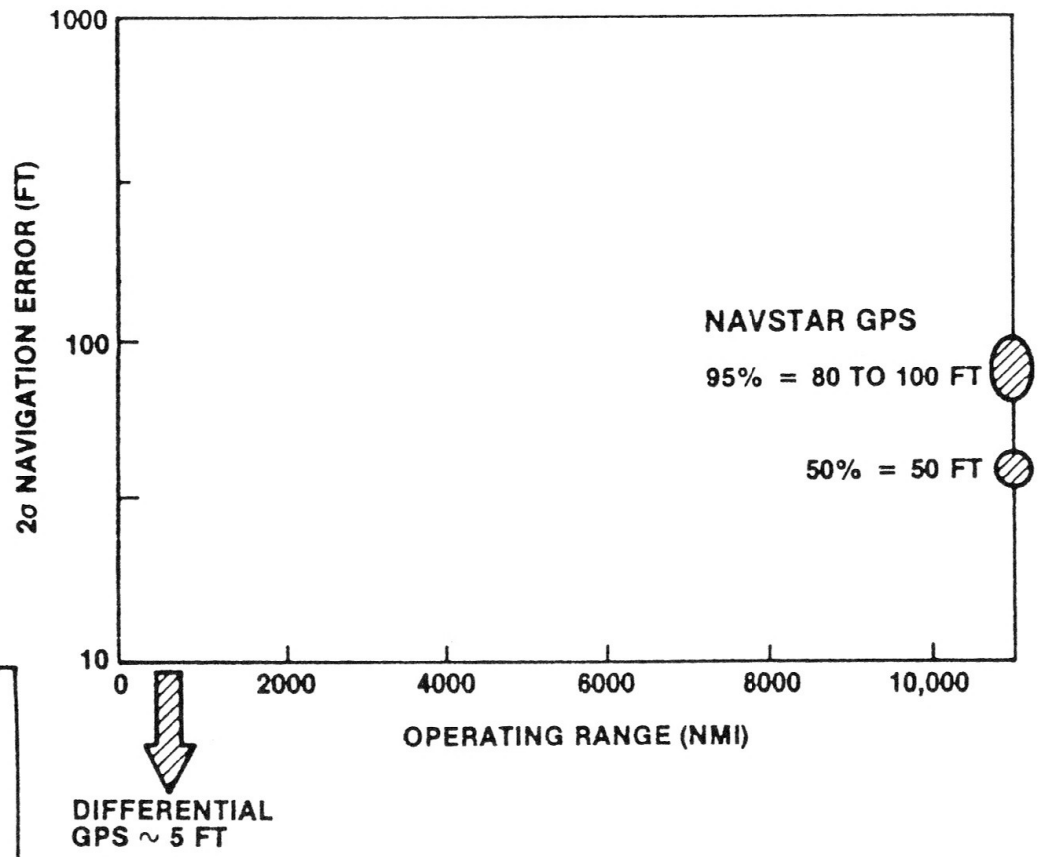


COMPUTE THE USER'S POSITION COORDINATES

$$(X_1 - U_X)^2 + (Y_1 - U_Y)^2 + (Z_1 - U_Z)^2 = (R_1 - C_B)^2$$
$$(X_2 - U_X)^2 + (Y_2 - U_Y)^2 + (Z_2 - U_Z)^2 = (R_2 - C_B)^2$$
$$(X_3 - U_X)^2 + (Y_3 - U_Y)^2 + (Z_3 - U_Z)^2 = (R_3 - C_B)^2$$
$$(X_4 - U_X)^2 + (Y_4 - U_Y)^2 + (Z_4 - U_Z)^2 = (R_4 - C_B)^2$$

FOUR EQUATIONS IN 4 UNKNOWNS SOLVE FOR THE CLOCK BIAS (C_B) AND THE USER'S POSITION COORDINATES (U_X, U_Y, AND U_Z)

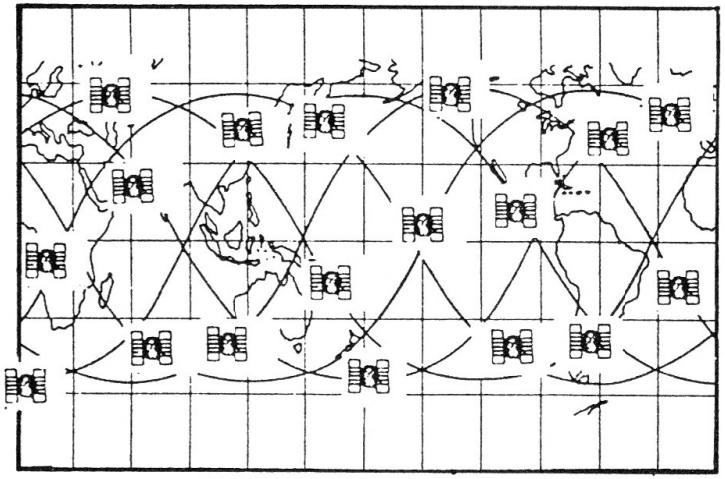
RANGE AND ACCURACY



THE NAVSTAR GPS

Ball Efratom Division

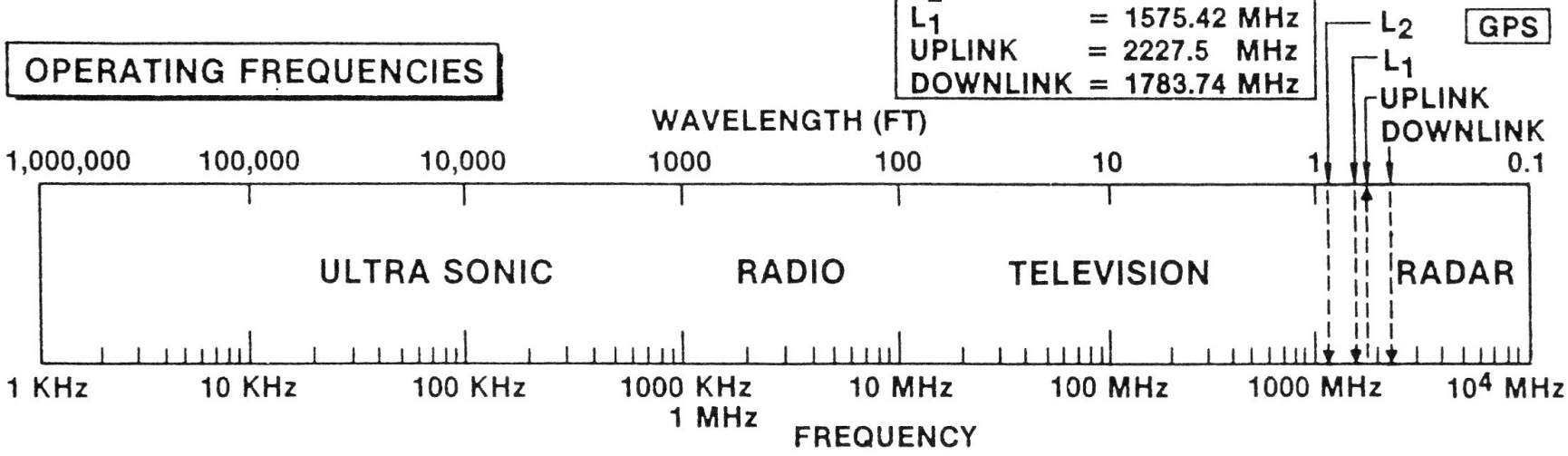
COVERAGE



SOME 13 SATELLITES NOW IN ORBIT. 18 TO 21 SATELLITE CONSTELLATION IN A FEW YEARS. PERFORMANCE EXPECTED TO EXCEED NEARLY ALL SPECIFICATIONS

OPERATING FREQUENCIES

L_2	= 1227.6 MHz
L_1	= 1575.42 MHz
UPLINK	= 2227.5 MHz
DOWNLINK	= 1783.74 MHz



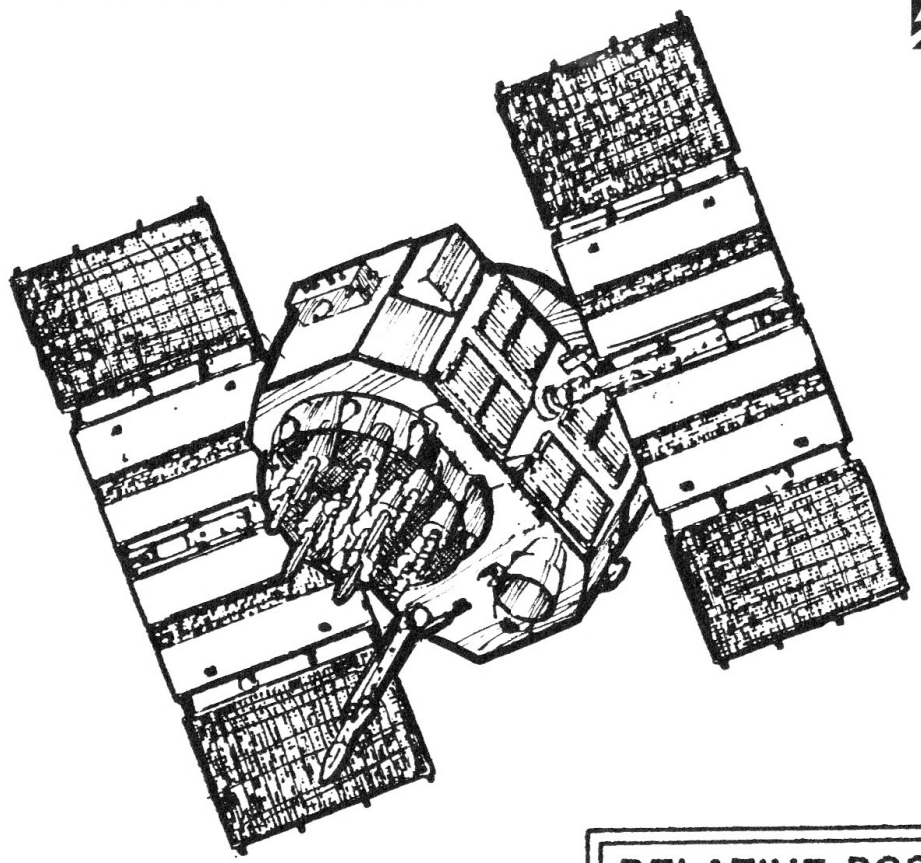
NAVSTAR GPS ACCURACY

Ball Efratom Division

POSITION
50 feet

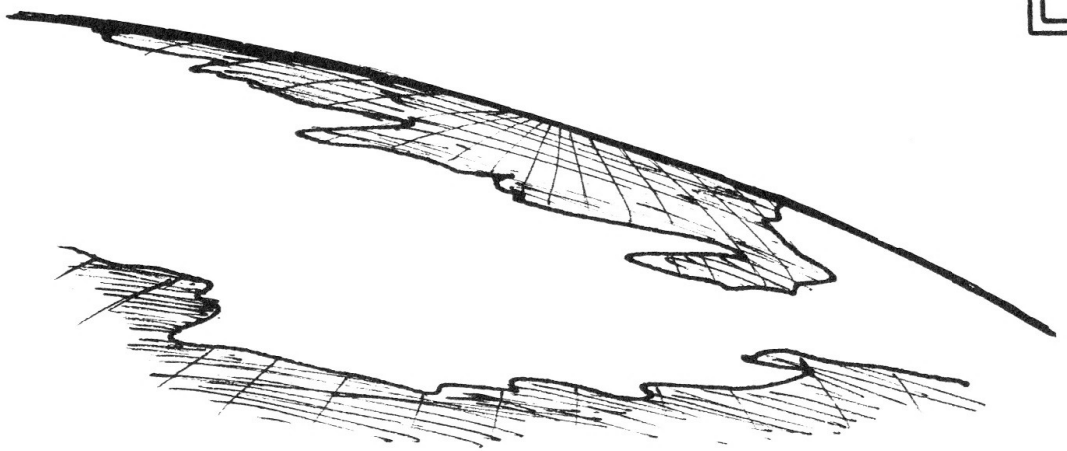
VELOCITY
0.3 ft/sec

TIME
100 nsec



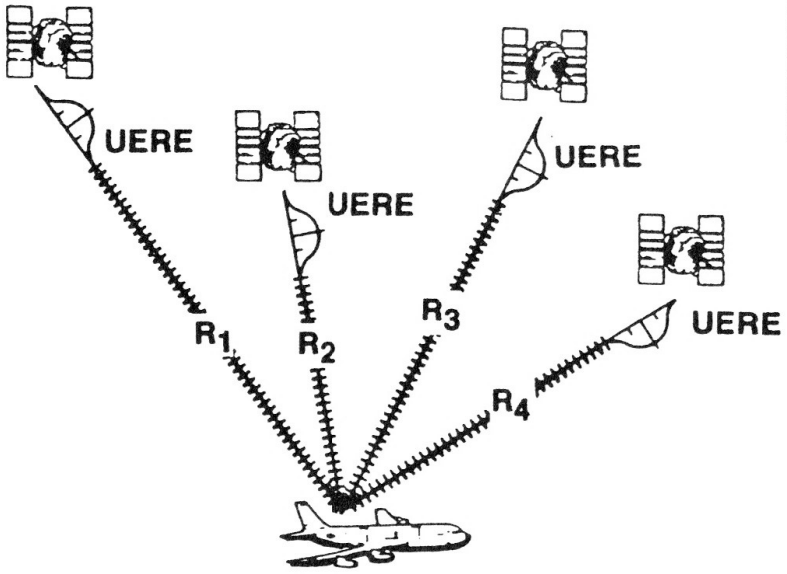
RELATIVE POSITION
10 TO 15 feet

RELATIVE TIME
3 TO 5 nsec



DETERMINING THE GPS NAVIGATION ACCURACY

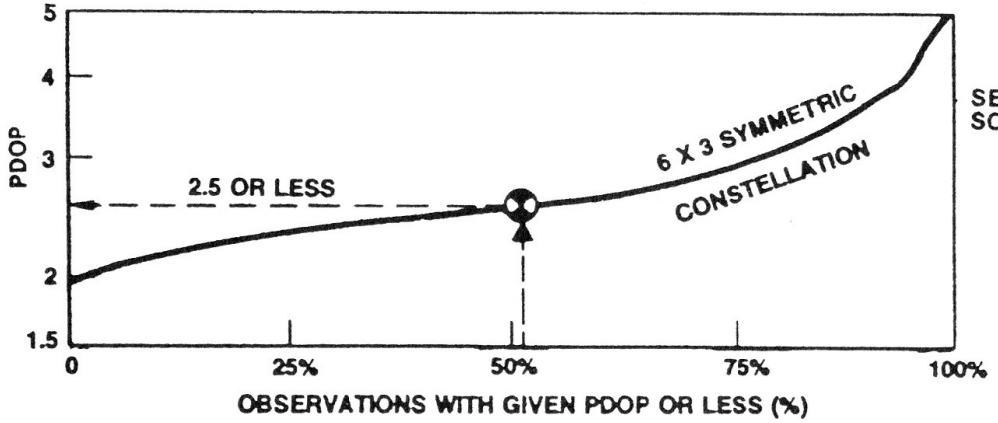
Ball Efratom Division

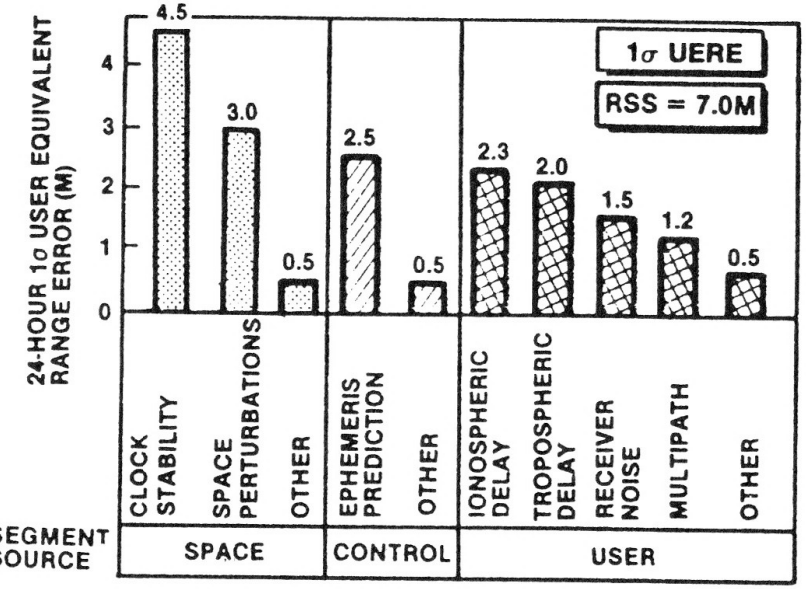


THE NAVIGATION ERROR DEPENDS UPON TWO FACTORS:

1. THE RANGE ERROR TO THE SATELLITES (UERE)
2. THE GEOMETRY OF THE SITUATION (GDOP OR PDOP)

GDOP = GEOMETRICAL DILUTION OF PRECISION
PDOP = POSITION DILUTION OF PRECISION

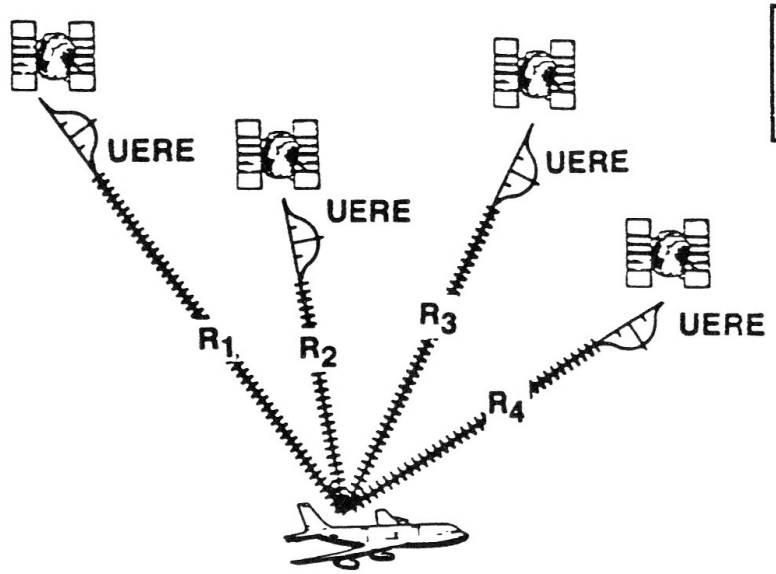




NAV ACCURACY = GDOP X UERE
= 2.5 X 7.0M
= 17M

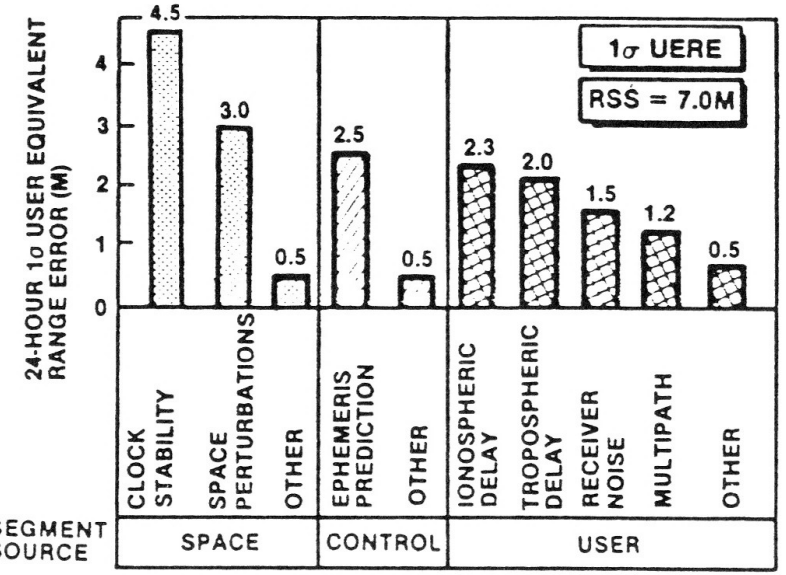
GPS CORRECTIONS TO THE NAVIGATION ACCURACY

Ball Efratom Division

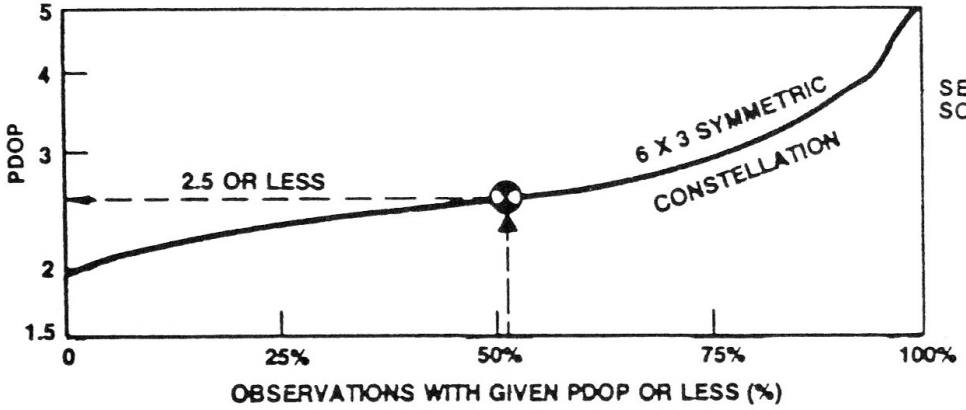


THE NAVIGATION ERROR DEPENDS UPON TWO FACTORS:

1. THE RANGE ERROR TO THE SATELLITES (UERE)
2. THE GEOMETRY OF THE SITUATION (GDOP OR PDOP)



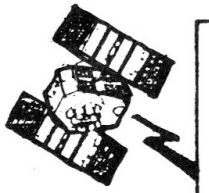
GDOP = GEOMETRICAL DILUTION OF PRECISION
PDOP = POSITION DILUTION OF PRECISION



NAV ACCURACY = GDOP X UERE
= 2.5 X 7.0M
= 17M

GPS CORRECTIONS TO THE NAVIGATION SOLUTION

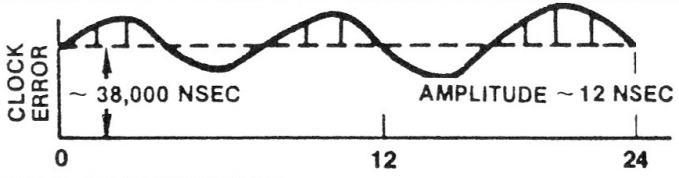
Ball Efratom Division



GPS SATELLITE

RELATIVISTIC CORRECTION

- SATELLITE CLOCKS PURPOSELY SET LOW BY 4.45×10^{-10} MHz



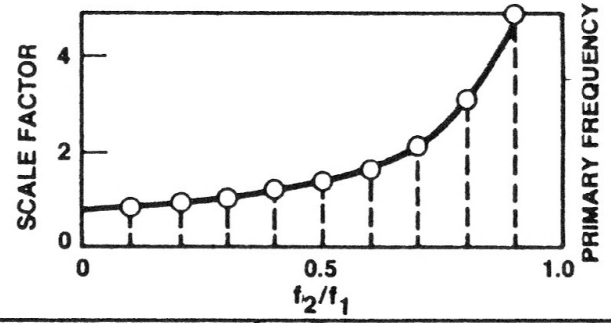
$$f_r = f_t\left\{1 + \frac{(\phi_t\phi_r)}{c^2} + 1/2\left[\frac{v_r^2}{c^2} - \frac{v_t^2}{c^2}\right] + \frac{K}{c}\left[\vec{V_t} - \vec{V_r}\right]\right.$$

GRAV. POTENT. GEN. RELATIVITY — SPECIAL RELATIV. SHIFTS — NORMAL DOPPER

IONOSPHERIC CORRECTION

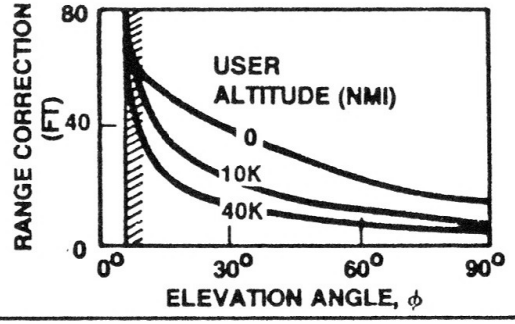
AT L_1: $R_1 = R_{true} + K/f_1^2$
AT L_2: $R_2 = R_{true} + K/f_2^2$

$$R_{true} = \frac{R_1 - (f_2/f_1)^2 R_2}{1 - (f_2/f_1)^2}$$



TROPOSPHERIC CORRECTION

$$\Delta R = \frac{-2.175e^{-0.1439H}}{\text{SIN}\,\phi}$$



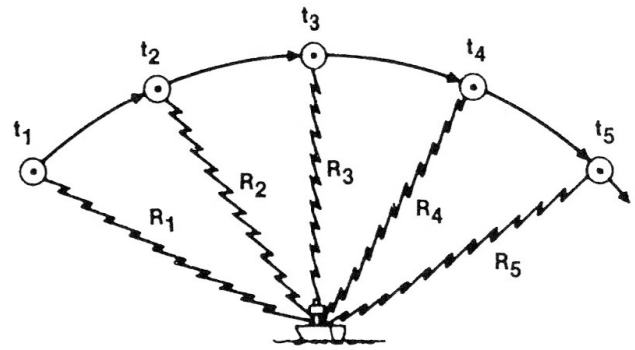
USER SET

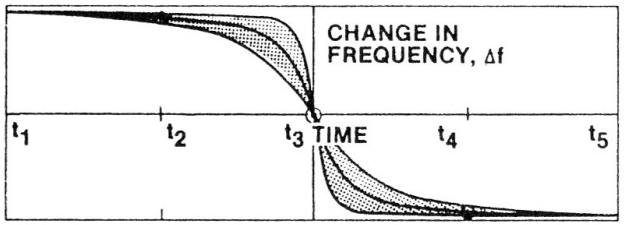
THE TRANSIT NAVIGATION SATELLITE

Ball Efratom Division

DESCRIPTION

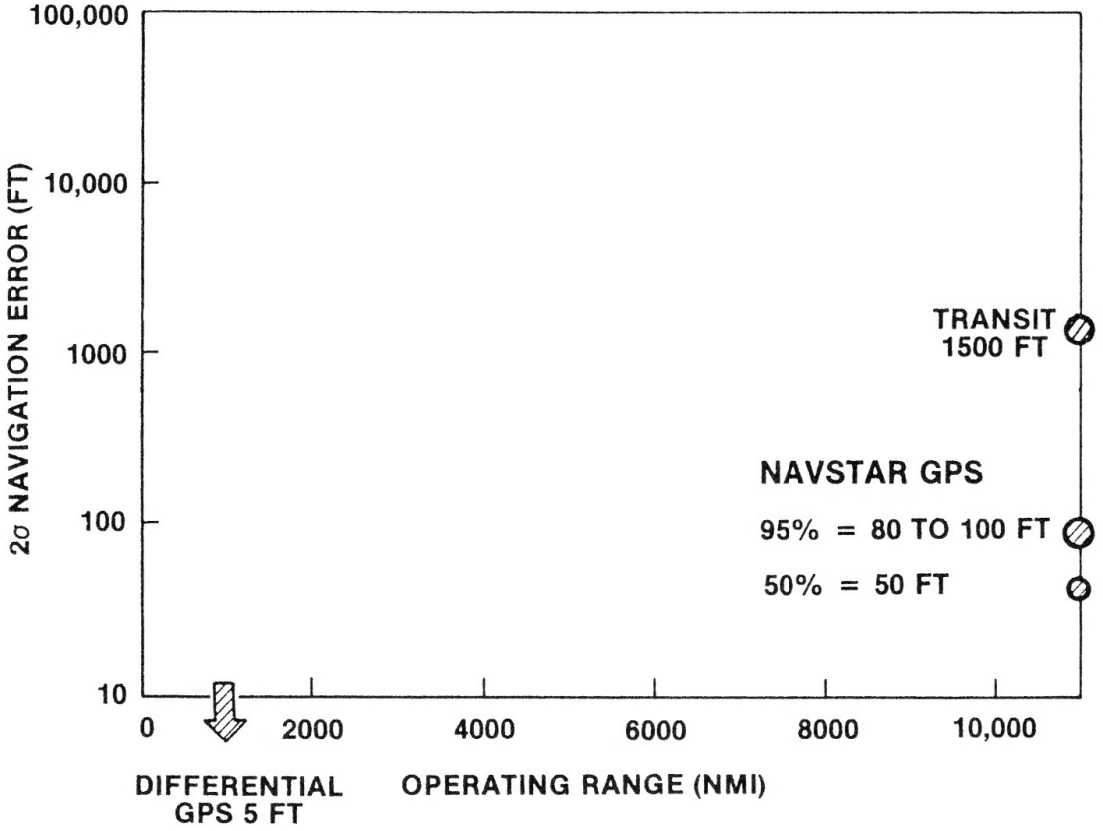
DOPPLER SHIFT:
LONGITUDE, LATITUDE





$$\Delta f \cong \frac{-fV^2t}{C\,(V^2t^2 + D^2)^{1/2}}$$

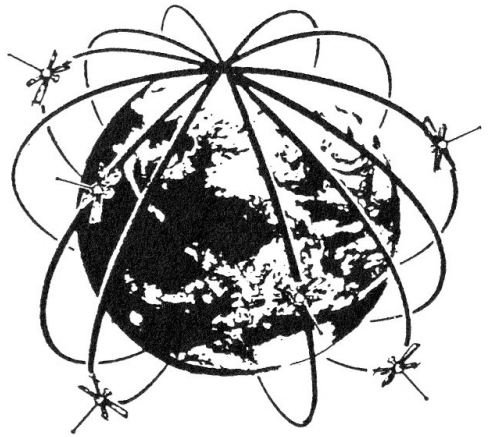
RANGE AND ACCURACY



THE TRANSIT NAVIGATION SATELLITE

Ball Efratom Division

COVERAGE

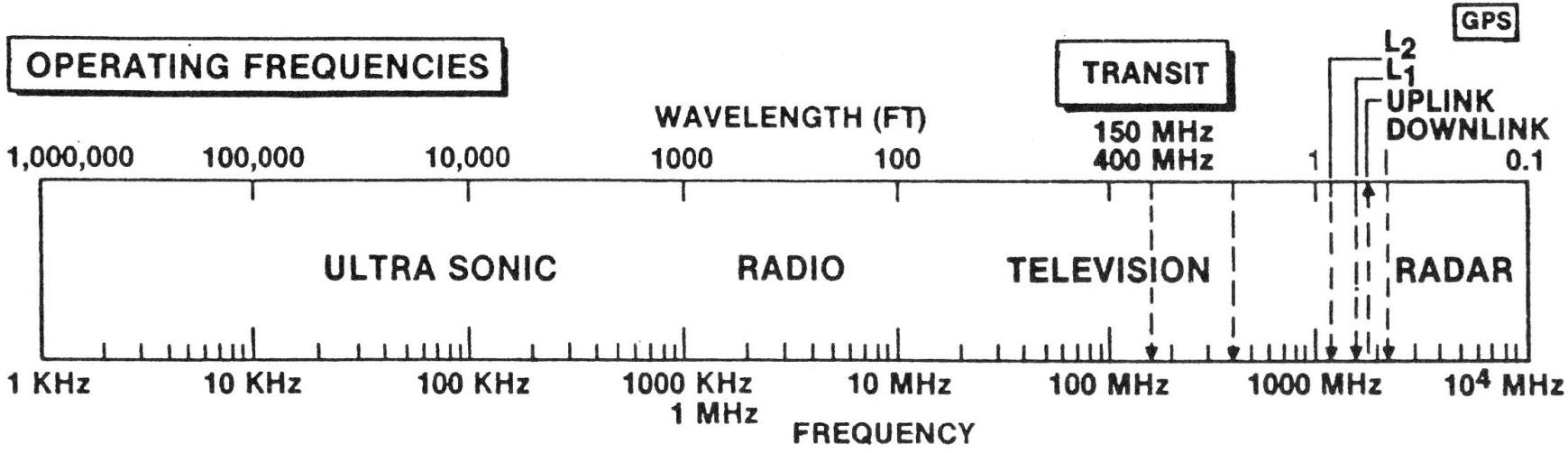


7 SATELLITES IN POLAR "BIRDCAGE" ORBITS PROVIDE GLOBAL FIXES 1/2 HOUR TO 2 HOURS APART.

STATUS

7 SATELLITES IN POLAR "BIRDCAGE" ORBITS, AND SOME IN SPACE STORAGE. >80,000 SETS IN USE WORLDWIDE. 80% ARE OWNED BY CIVILIAN USERS. EXPECTED TO BE PHASED OUT IN 1996.

OPERATING FREQUENCIES

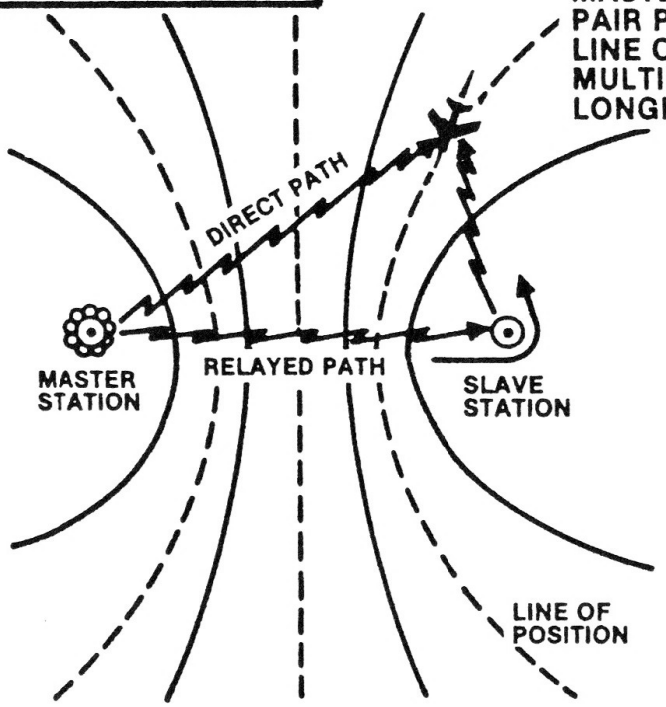


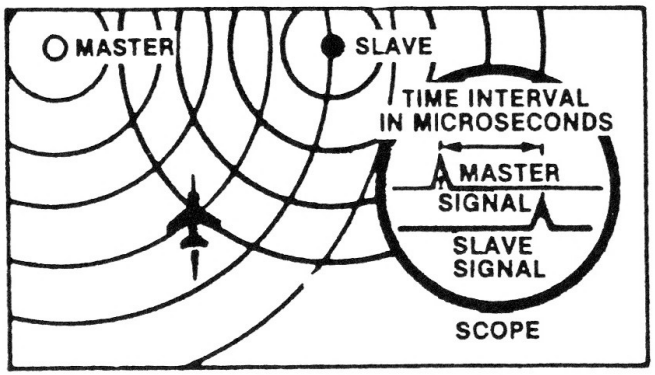
LORAN-C

Ball Efratom Division

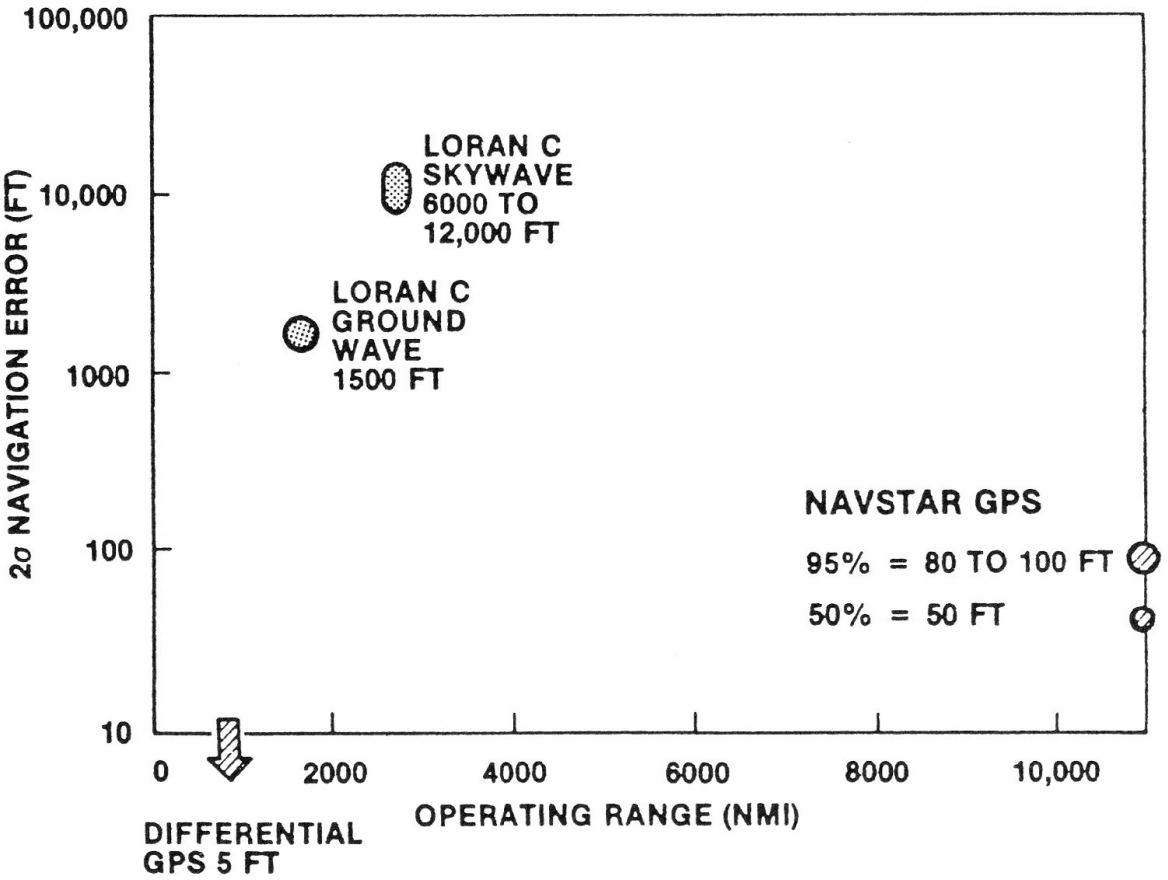
DESCRIPTION

MASTER-SLAVE TRANSMITTER PAIR PROVIDES HYPERBOLIC LINE OF POSITION. MULTIPLE PAIRS YIELD LONGITUDE, LATITUDE





RANGE AND ACCURACY

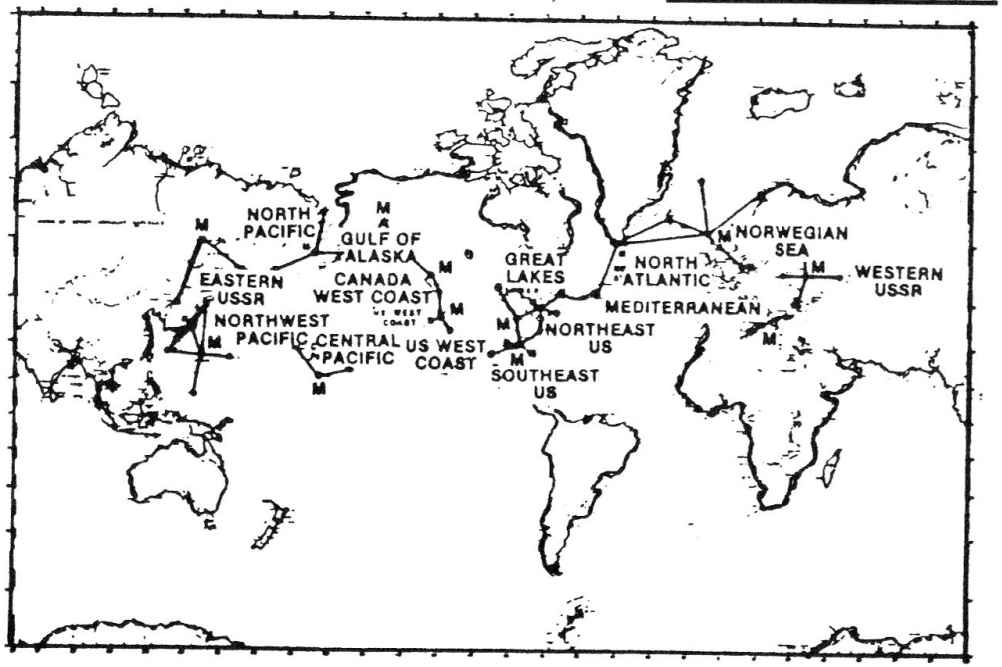


LORAN-C

Ball Efratom Division

COVERAGE

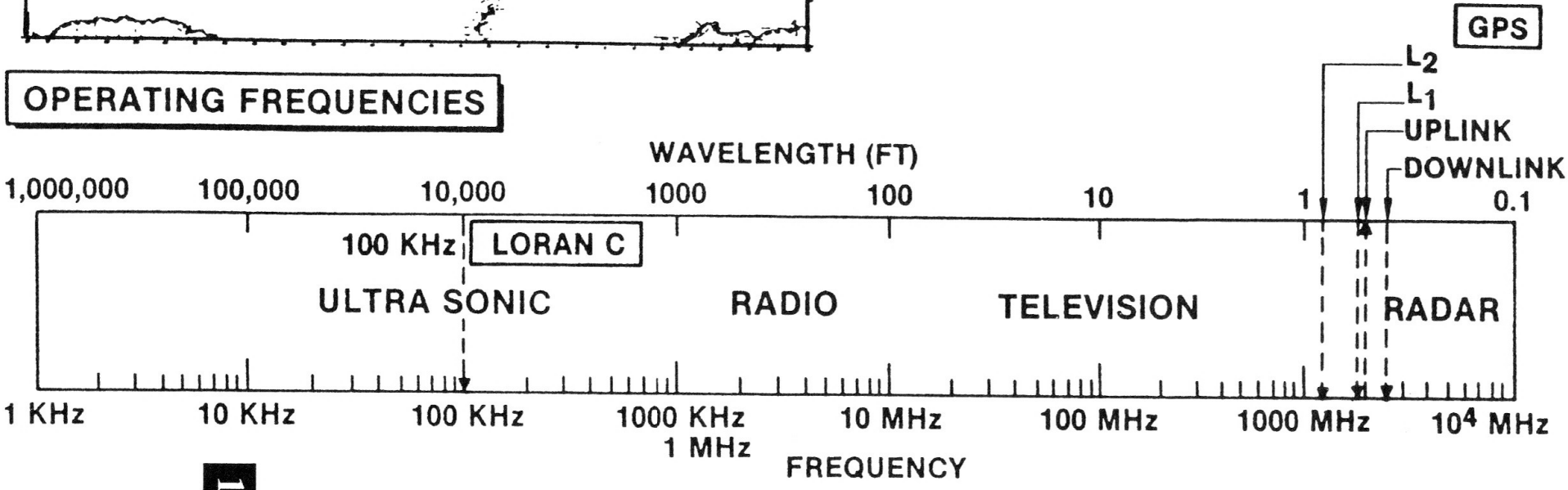
EIGHT LORAN-C CHAINS WITH MORE THAN 34 OPERATING TRANSMITTERS PRESENTLY PROVIDE COVERAGE FOR ABOUT 10% OF THE GLOBE, AND NOW TOTAL USA COVERAGE.



STATUS

WORLDWIDE THERE ARE ESTIMATED TO BE AS MANY AS 60,000 CIVIL LORAN C USERS. MILITARY PLANS TO SWITCH OVER TO THE GPS BY THE EARLY 1990'S.

OPERATING FREQUENCIES



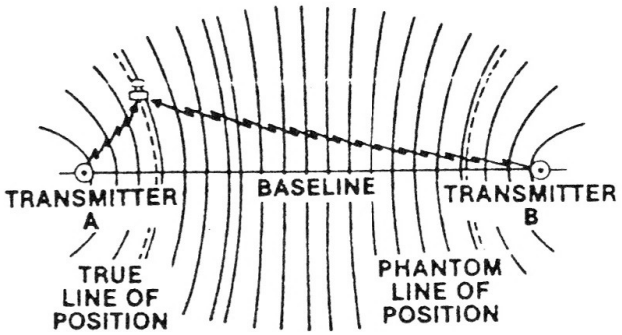
14.21

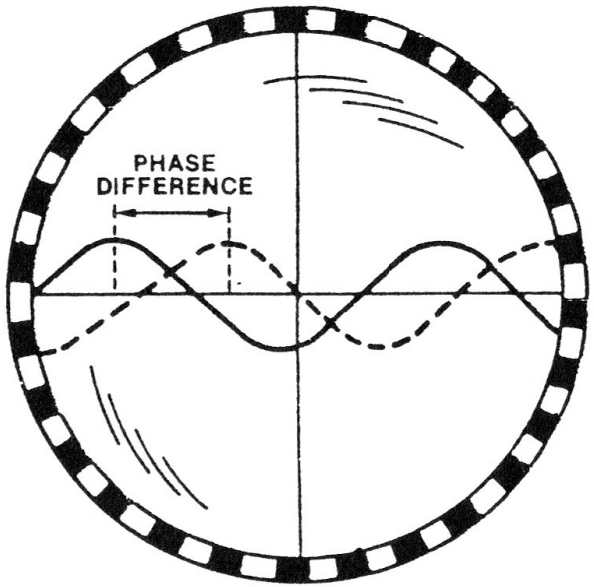
OMEGA

Ball Efratom Division

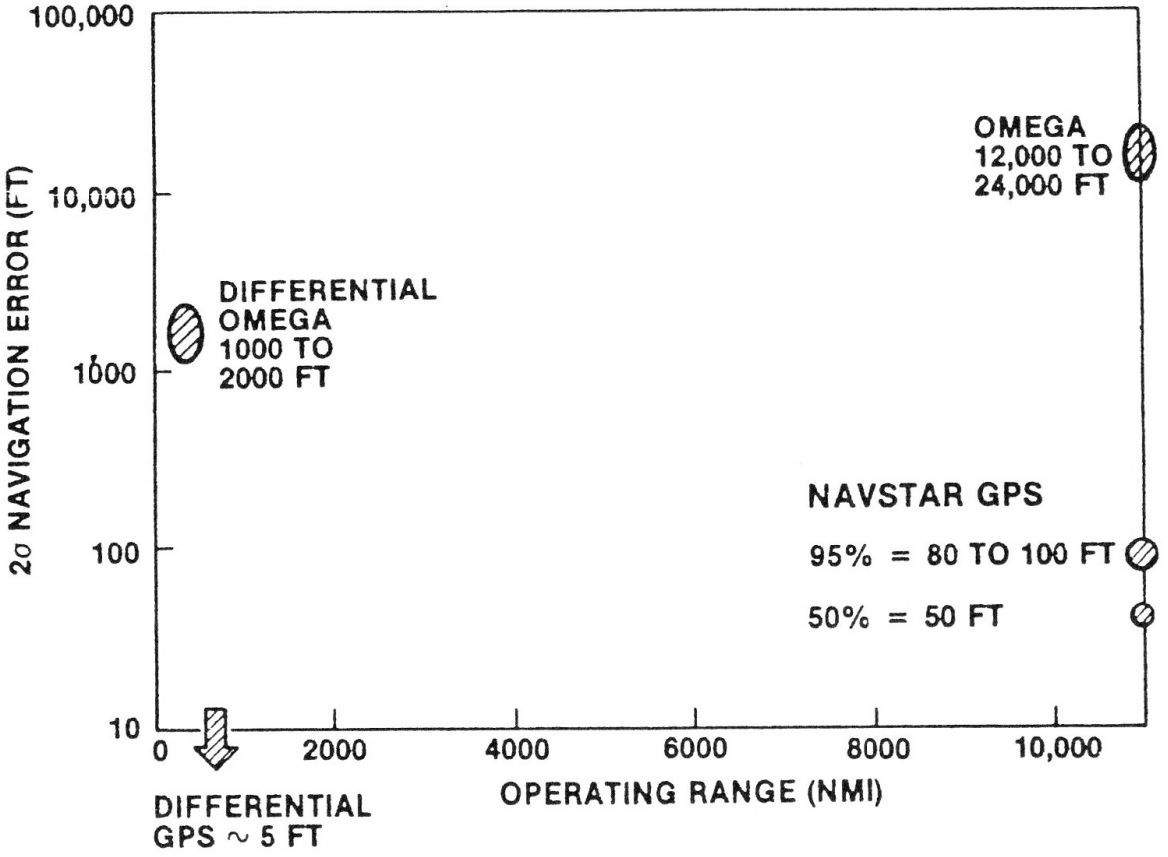
DESCRIPTION

HYPERBOLIC RANGING USING PHASE DIFFERENCE MEASUREMENTS. MULTIPLE TRANSMITTER PAIRS YIELD LONGITUDE, LATITUDE





RANGE AND ACCURACY

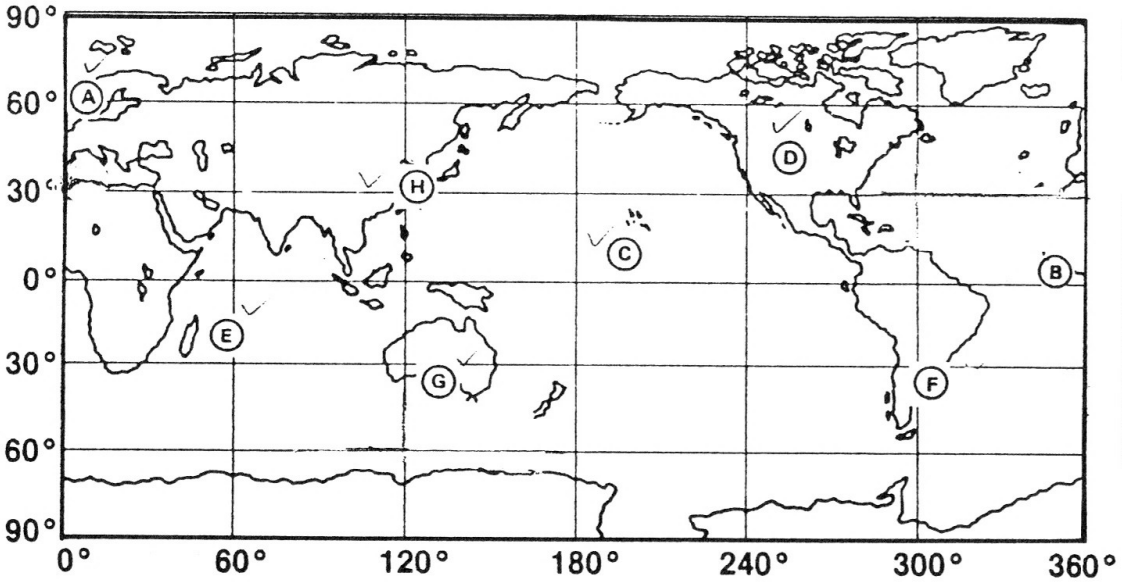


OMEGA

Ball Efratom Division

COVERAGE

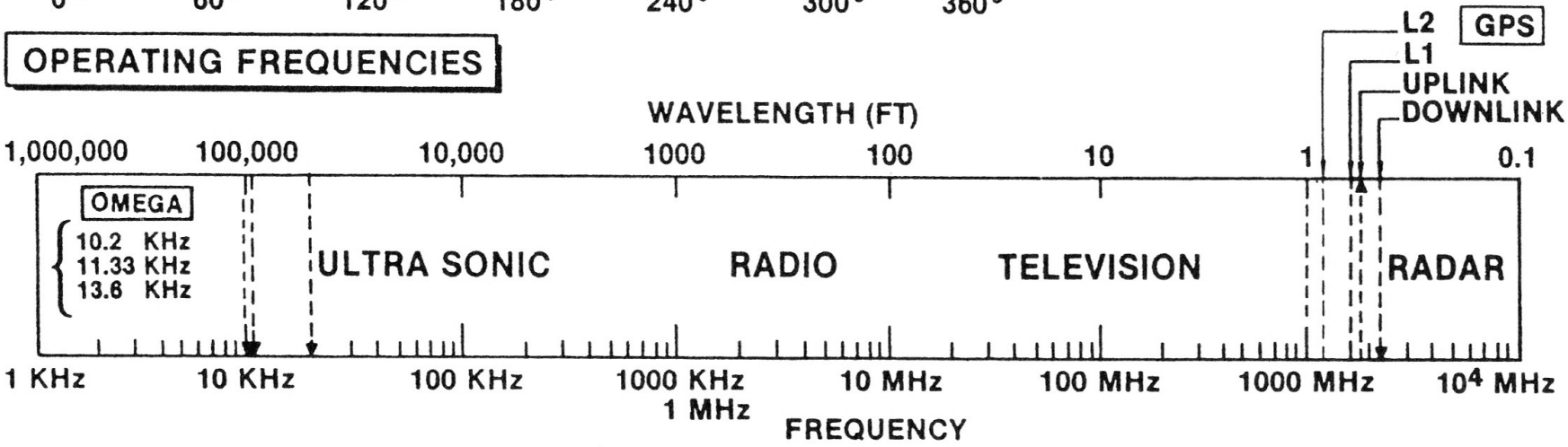
EIGHT VLF TRANSMITTING STATIONS
PROVIDE 88% GLOBAL COVERAGE BY DAY
AND 98% COVERAGE BY NIGHT



STATUS

(A) NORWAY	(E) LA REUNION ISL.
(B) LIBERIA	(F) ARGENTINA
(C) HAWAII	(G) AUSTRALIA
(D) N. DAKOTA	(H) JAPAN

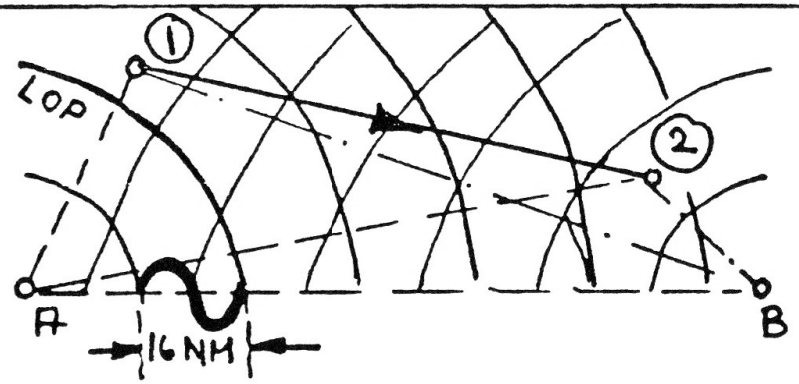
OPERATING FREQUENCIES



OMEGA/VLF NAVIGATION

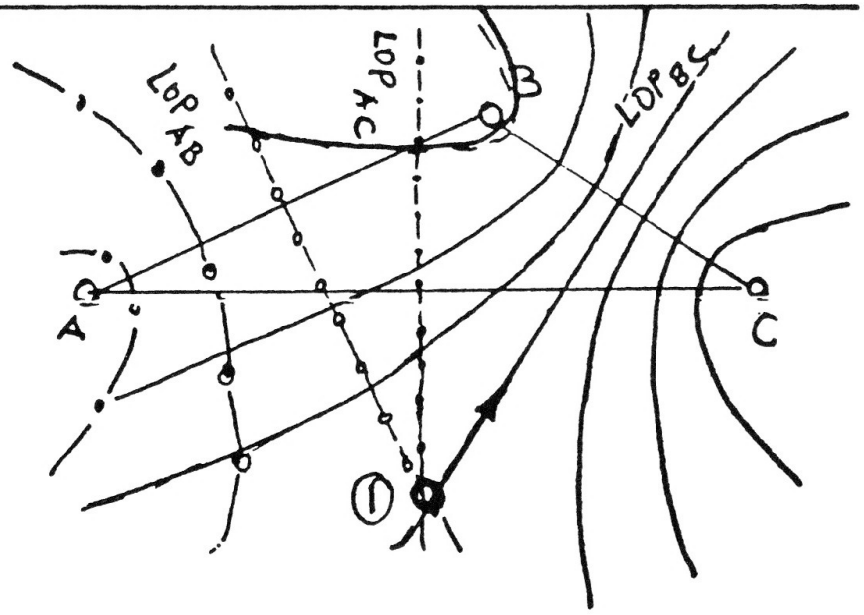
Ball Efratom Division

RHO - RHO NAV



- POSITION A, B, AND (1) = START KNOWN
- POSITION FIX IS ACHIEVED BY LANE COUNT + CENTILANE COUNT USING PHASE MEASUREMENTS FROM 2 TRANSMITTERS (A,B) AGAINST ON-BOARD ATOMIC OSCILLATOR

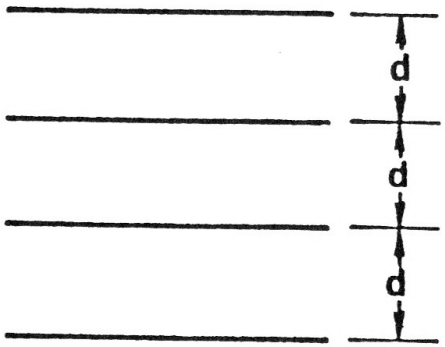
HYPERBOLIC NAV



- POSITION A, B, C, ARE KNOWN
- HYPERBOLA ARE LANES OF CONSTANT DISTANCE OR PHASE DIFFERENCE BETWEEN 2 STATIONS. 3 TRANSMITTER STATIONS ARE REQUIRED FOR POSITION FIX. NO ATOMIC CLOCK REQUIRED

OMEGA'S LANE AMBIGUITIES

Ball Efratom Division



A LANE IS THE DISTANCE, d, WHICH CAUSES THE PHASE DIFFERENCE $\Delta\Phi$ OF THE SIGNALS OBTAINED FROM TWO TRANSMITTERS TO CHANGE BY 360°

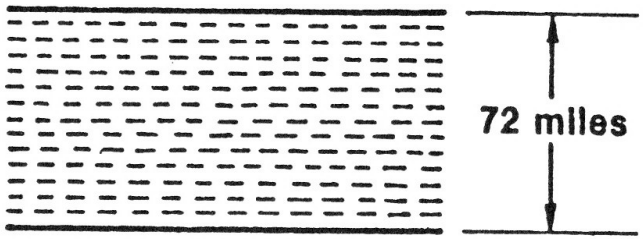
LANE AMBIGUITIES CAN BE A PROBLEM

WORKING WITH f = 10.2 kHz, WE HAVE:

$$\text{APPROXIMATE LANE WIDTH} = \frac{C}{2f} = \frac{186{,}000 \text{ mi/sec}}{2(10{,}200 \text{ cycles/sec})} \sim 8 \text{ miles}$$

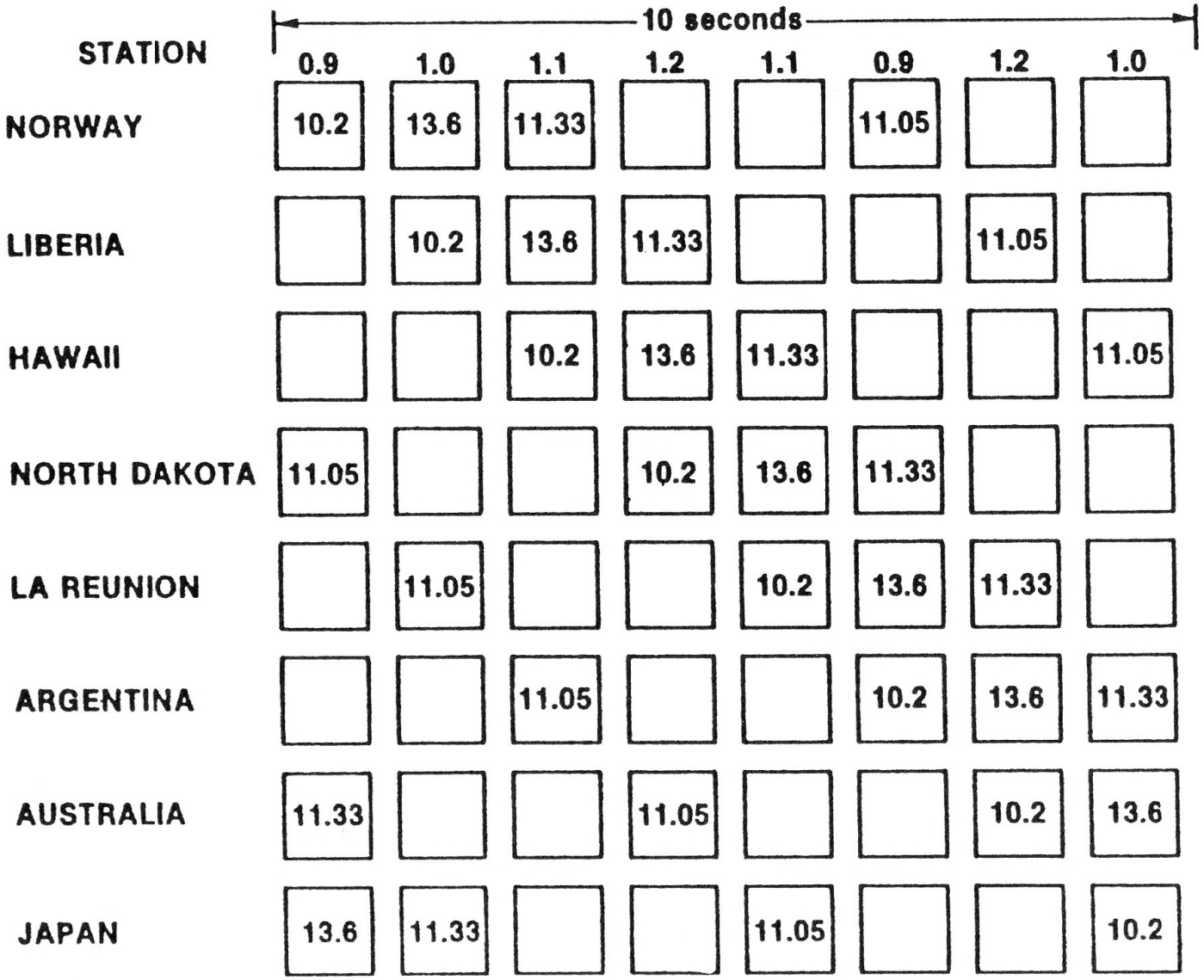
SO THE USER HAS TO "KNOW" WHERE HE IS WITHIN 8 miles

THE OTHER TRANSMISSION FREQUENCIES RAISE THE LANE AMBIGUITY TO 72 miles



OMEGA USES STAGGERED TDMA TRANSMISSIONS FOR TRANSMITTER IDENTIFICATION

Ball Efratom Division



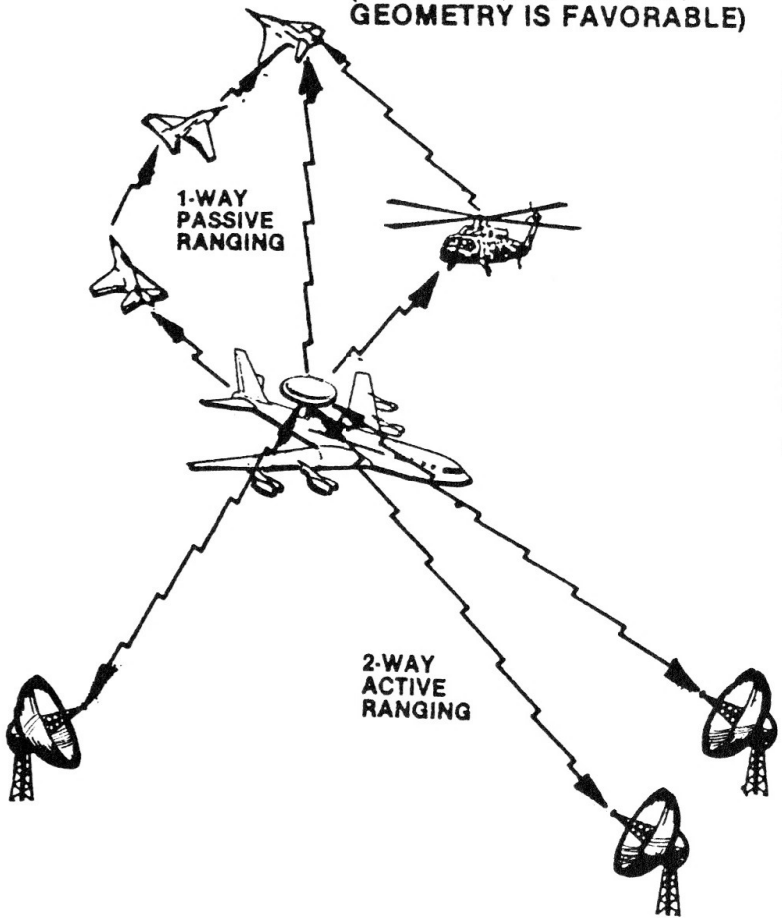
THE USER MUST SYNCHRONIZE HIS CLOCK PRIOR TO DEPARTURE: COMPUTER MAKES AUTOMATIC VERIFICATIONS

JTIDS RELNAV
(JOINT TACTICAL INFORMATION & DATA SYSTEM)

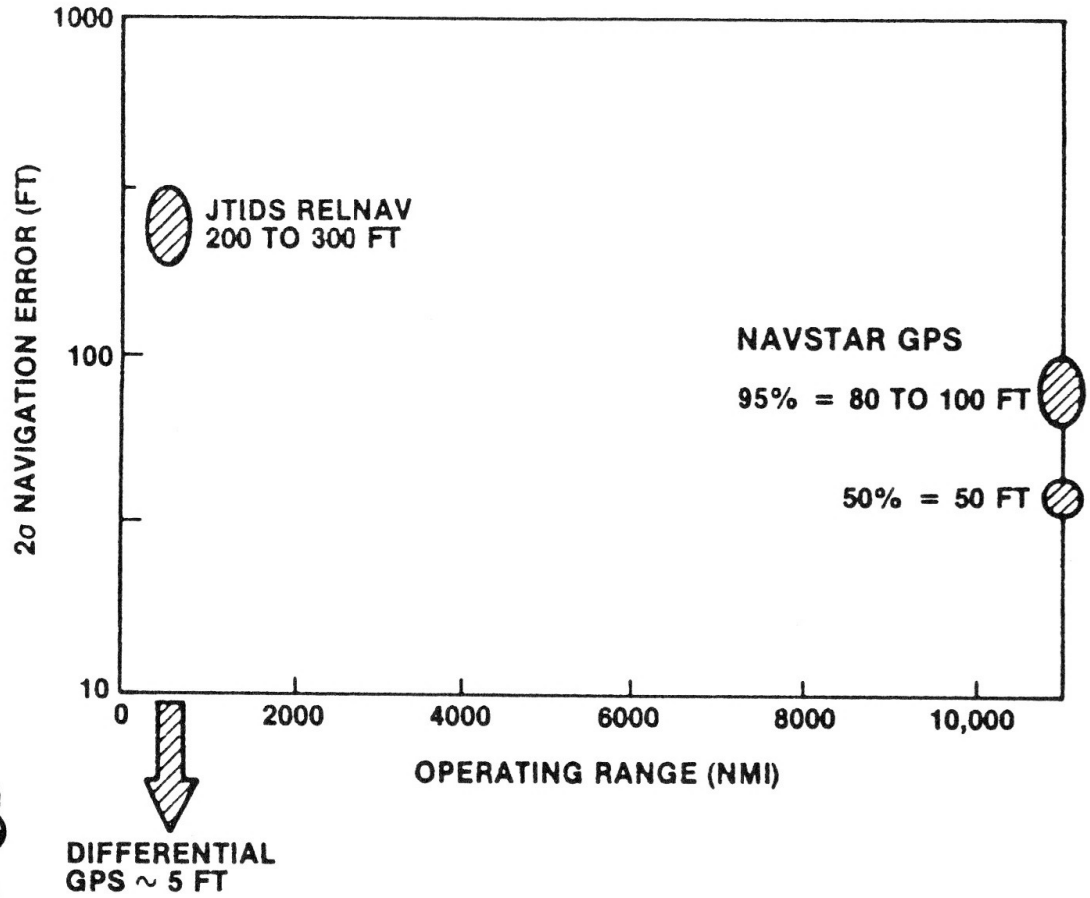
Ball Efratom Division

DESCRIPTION

ACTIVE AND PASSIVE
SPHERICAL RANGING
2D POSITION
2D VELOCITY
(ALTITUDE AVAILABLE IF
GEOMETRY IS FAVORABLE)



RANGE AND ACCURACY

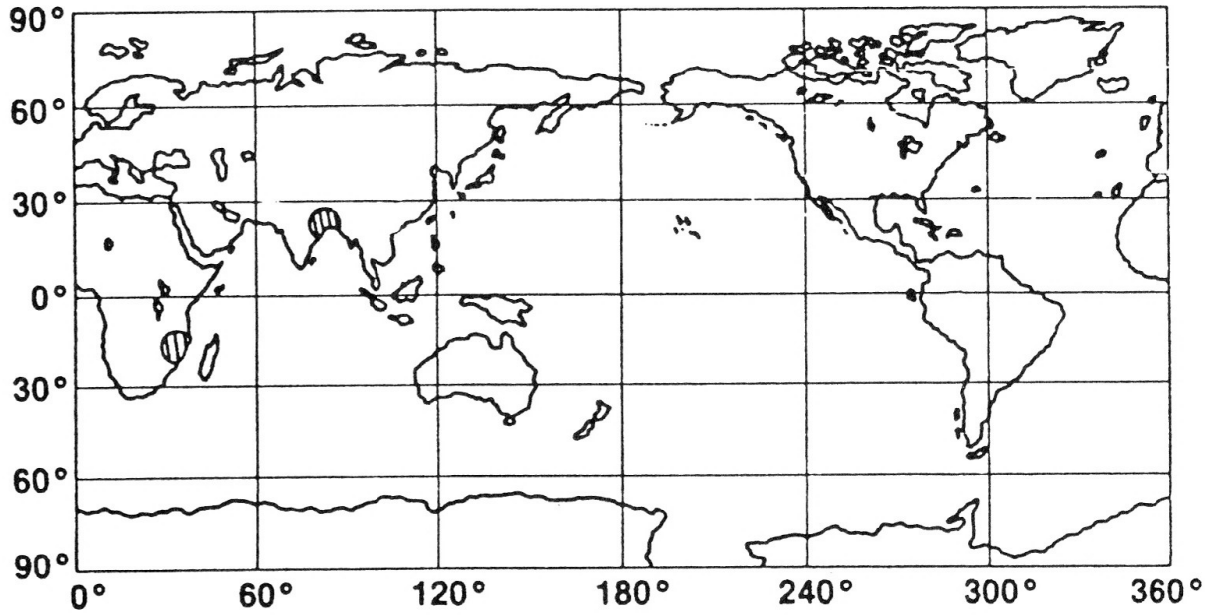


JTIDS RELNAV

Ball Efratom Division

COVERAGE

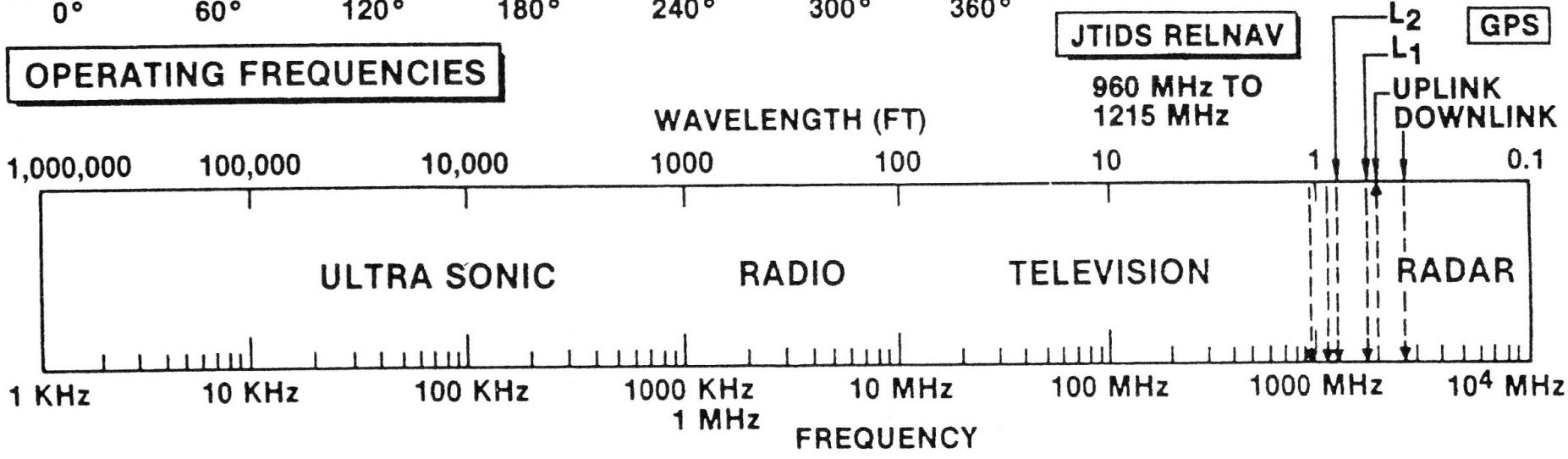
TEMPORARY COVERAGE FOR LOCAL BATTLE GROUPS ONLY. DATA RELAYS ALLOW MEDIUM OPERATING RANGES



STATUS

RELATIVE NAVIGATION USED IN CONJUNCTION WITH THE COMMUNICATION ASPECTS OF THE JTIDS.

OPERATING FREQUENCIES

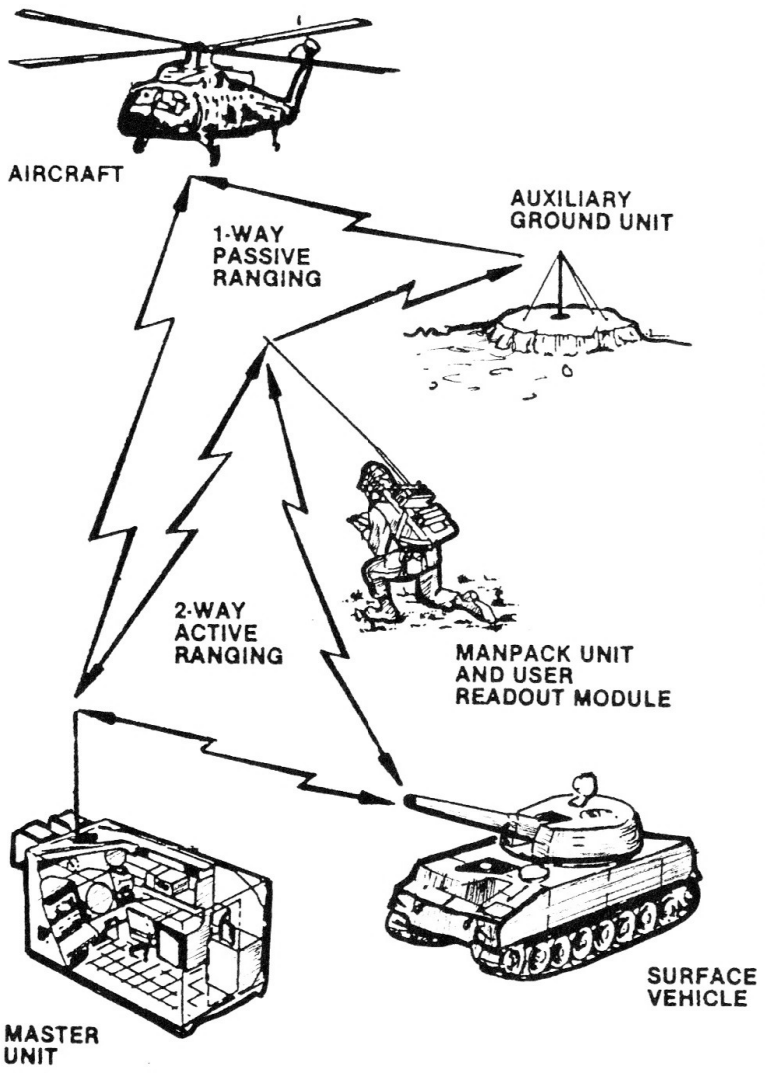


PLRS
(POSITION LOCATION AND RANGING SYSTEM)

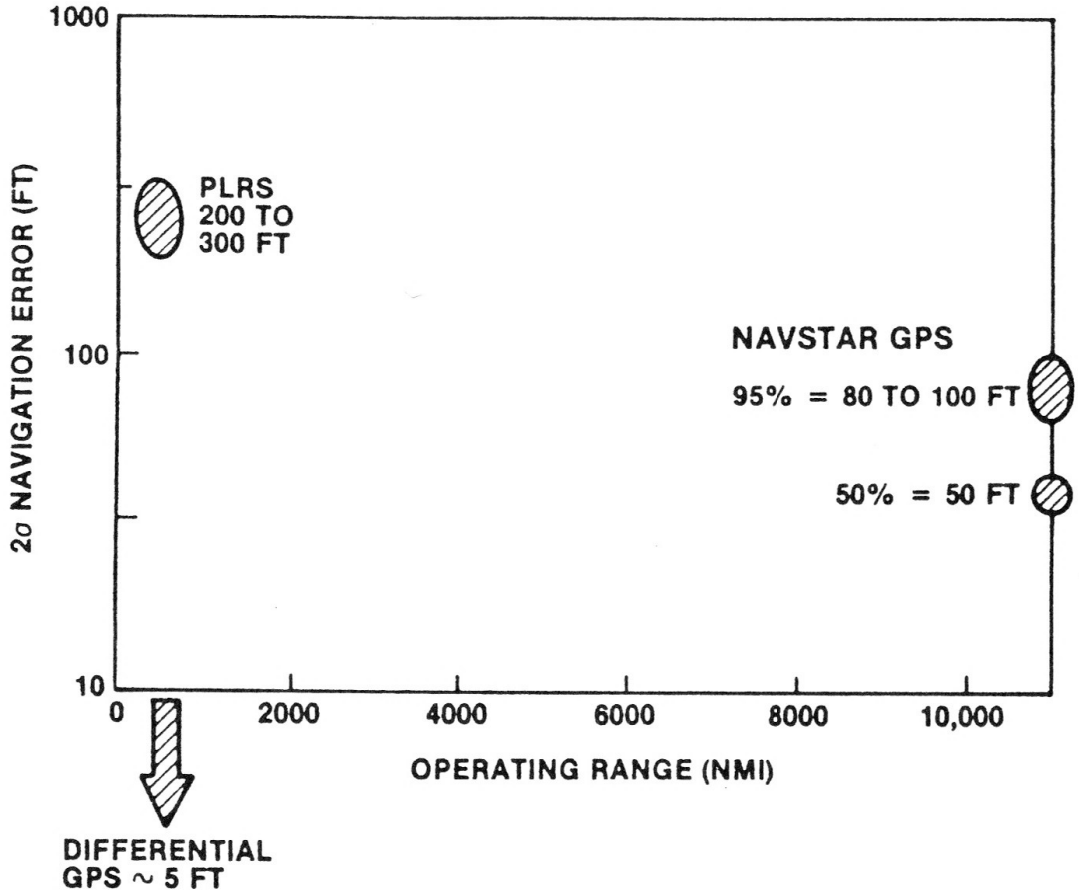
Ball Efratom Division

DESCRIPTION

ACTIVE AND PASSIVE SPHERICAL RANGING. PROVIDES 2D POSITION



RANGE AND ACCURACY

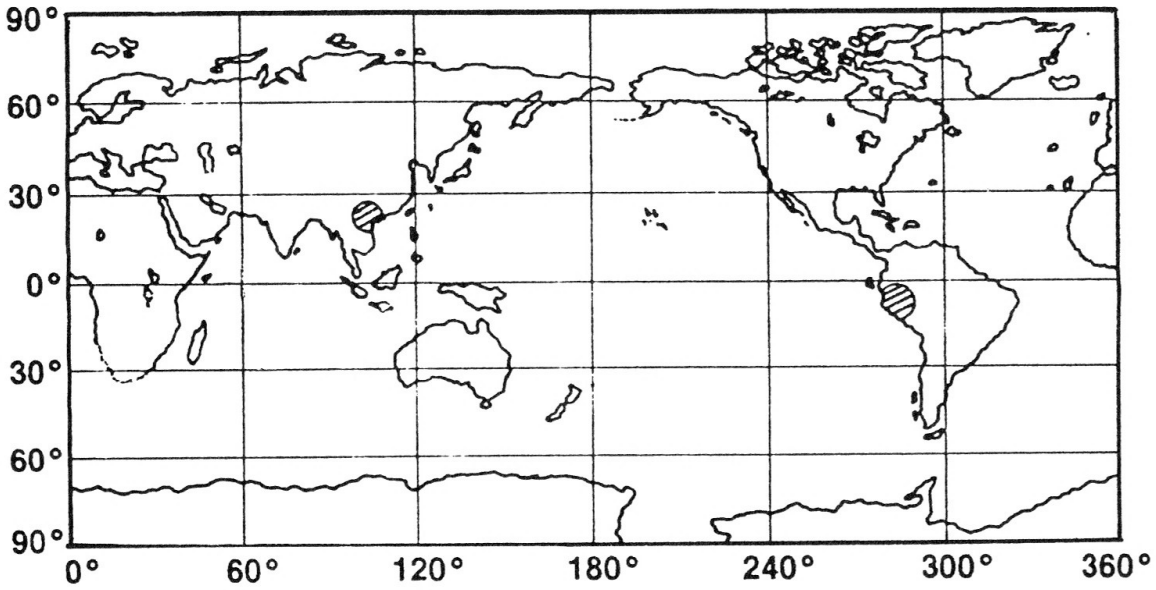


PLRS

Ball Efratom Division

COVERAGE

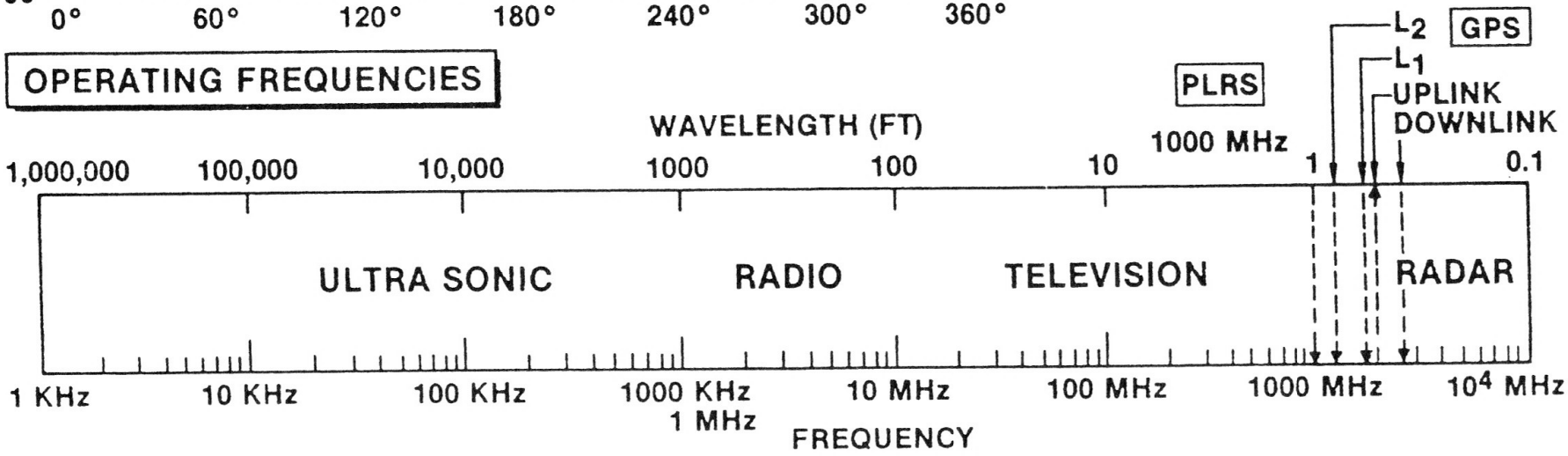
TEMPORARY COVERAGE FOR
LOCAL BATTLE GROUPS ONLY



STATUS

FOR USE BY THE ARMY IN LOCAL BATTLEFIELD AREA IN CONJUNCTION WITH THEIR COMMUNICATION AND INFORMATION DISTRIBUTION NETWORKS. (JTIDS)

OPERATING FREQUENCIES



WHY USE ATOMIC OSCILLATORS FOR NAVIGATION?

Rf Travels The Speed Of Light; Or	~186,000 miles/sec ~1 ft/ nanosec
A Very Good Quartz Oscillator	~1E-9 offset from environments and ~1E-10 aging/day Causes: ~100 microsec time error in a day or ~100,000 ft. position error (~19 miles)
An Atomic Oscillator (Rubidium)	~1E-10 offset from environments and ~3E-13 aging/day Causes: ~9 microsec time error in a day or ~9000 ft. position error (~1.7 miles)

SECURE-AJ COMMUNICATIONS AND THE OSCILLATOR

- The Spread Spectrum Technology
- Mechanizing The Precision Oscillator In Command, Control And Communications Systems

SPREAD SPECTRUM*

- Spread Spectrum Modulation results in a WIDEBAND, LOW POWER DENSITY Signal which has statistical properties of random noise

- The transmitted signal is not readily detected or recognized by conventional passive countermeasures; hence LOW DETECTABILITY

- Recovery of the baseband information must be accomplished through CORRELATION WITH AN EXACT REPLICA of the transmitted signal, thus denying the casual listener the baseband information

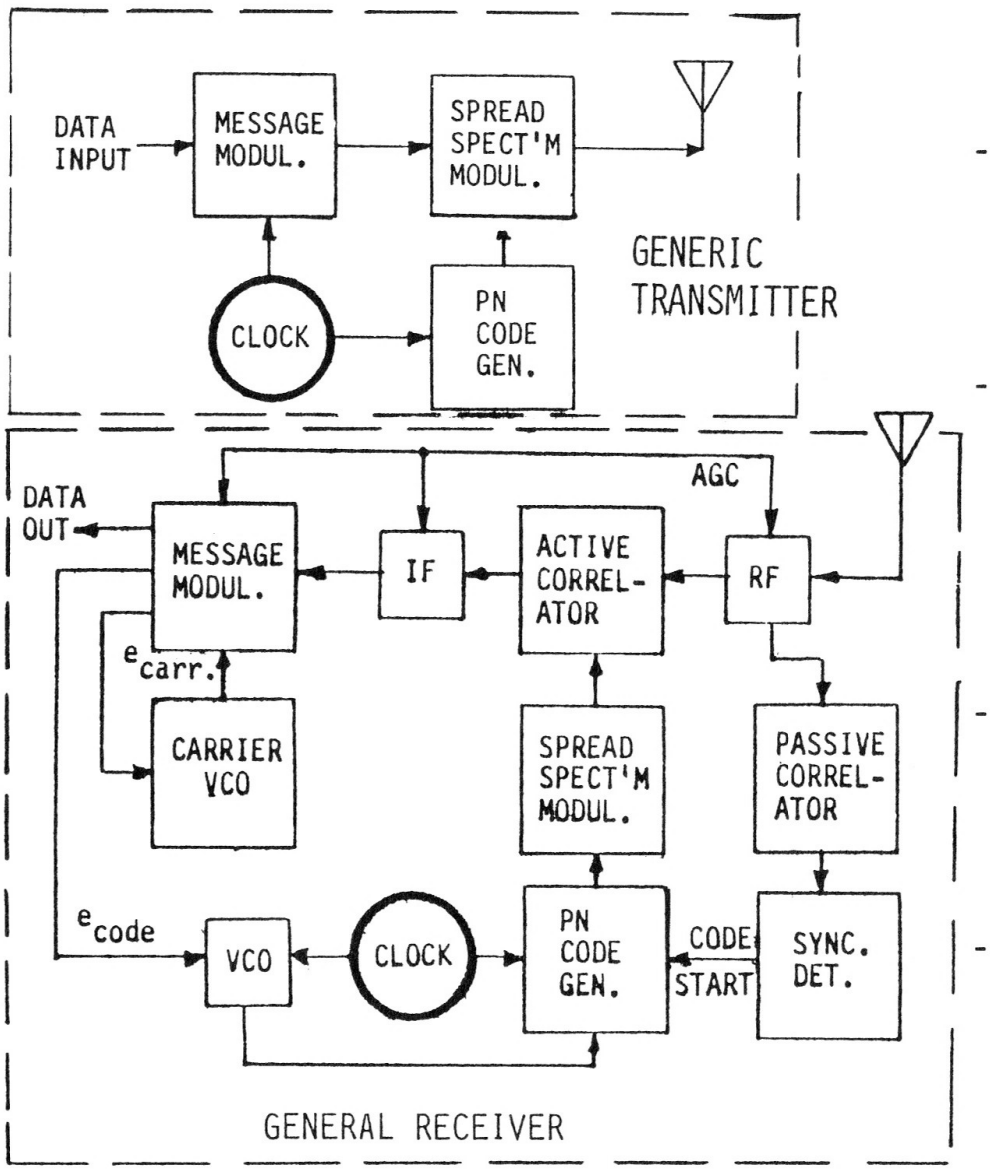
- Thus, Spread Spectrum Modulation provides JAM-RESISTANCE, INFORMATION PRIVACY, SELECTIVE CALLING and TRANSMITTER IDENTIFICATION capability

THE INTENSITY OF THESE ADVANTAGES DEPENDS LARGELY ON THE PRECISION OF THE OSCILLATOR

*Some material taken from "Spread Spectrum Applications and State-of-the-Art Equipment", MRL contr. no. MX-TM-3134-72, Agard Lecture Series no. 58, Magnavox APD, Dr. C.R.Cahn, unclassified.

BASIC SPREAD SPECTRUM SYSTEM

Ball Efratom Division



Spread Spectrum Modulation produces a signal whose bandwidth occupancy is expanded to be much wider than the message bandwidth

Common Techniques for this are:

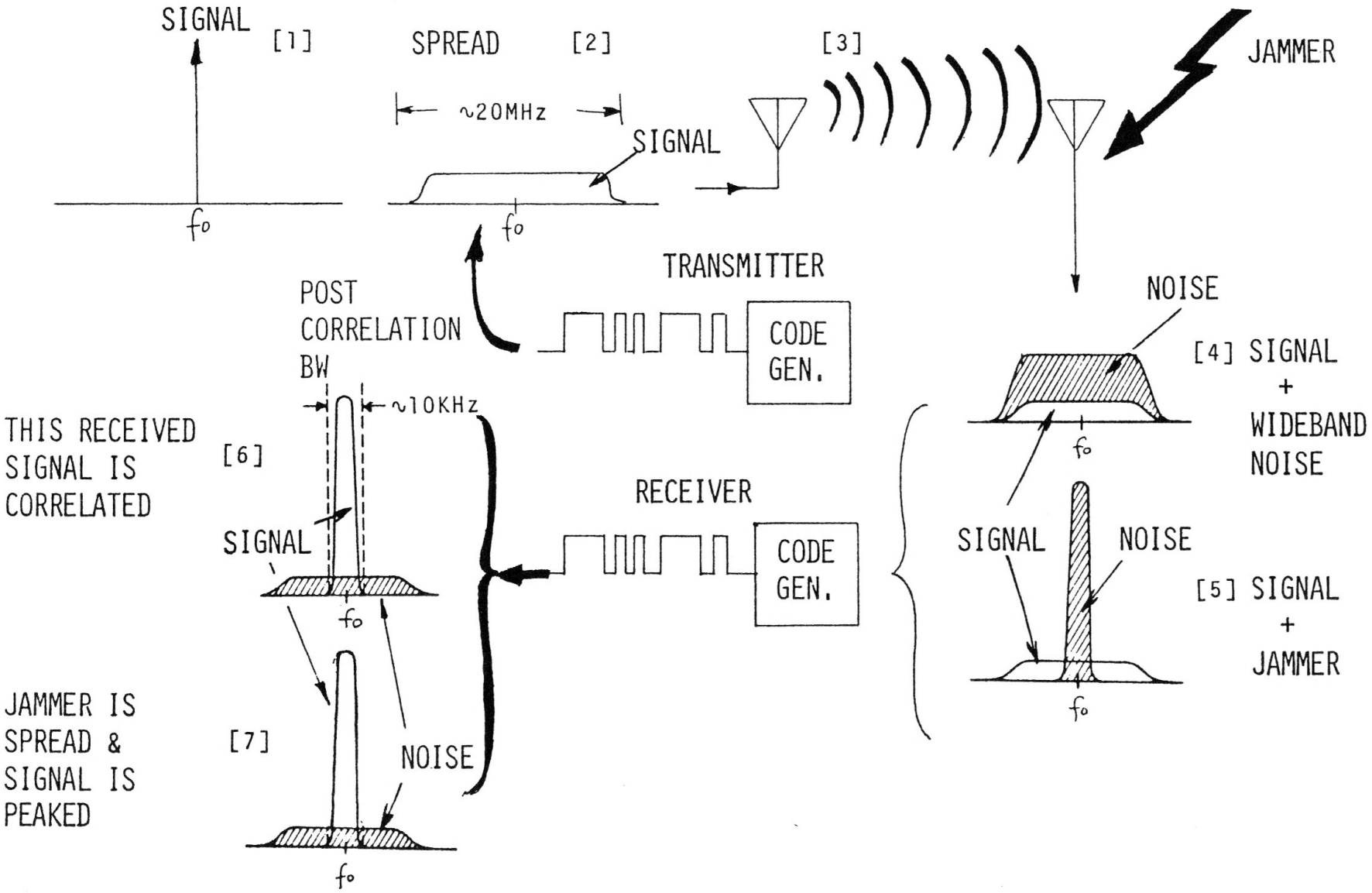
PN or PRN - PSEUDO RANDOM NOISE
FH - FREQUENCY HOPPING
TH - TIME HOPPING
or hybrids of these techniques

PN CODE is the basis for Spread Spectrum, where a RANDOM SEQUENCE OF BINAR DIGITS can be reproduced by the authorized user.

A HIGHLY STABLE OSCILLATOR is needed and some knowledge of propagation delays in order for receiver to initially acquir synchronization (unless a short, repetitive code is used)

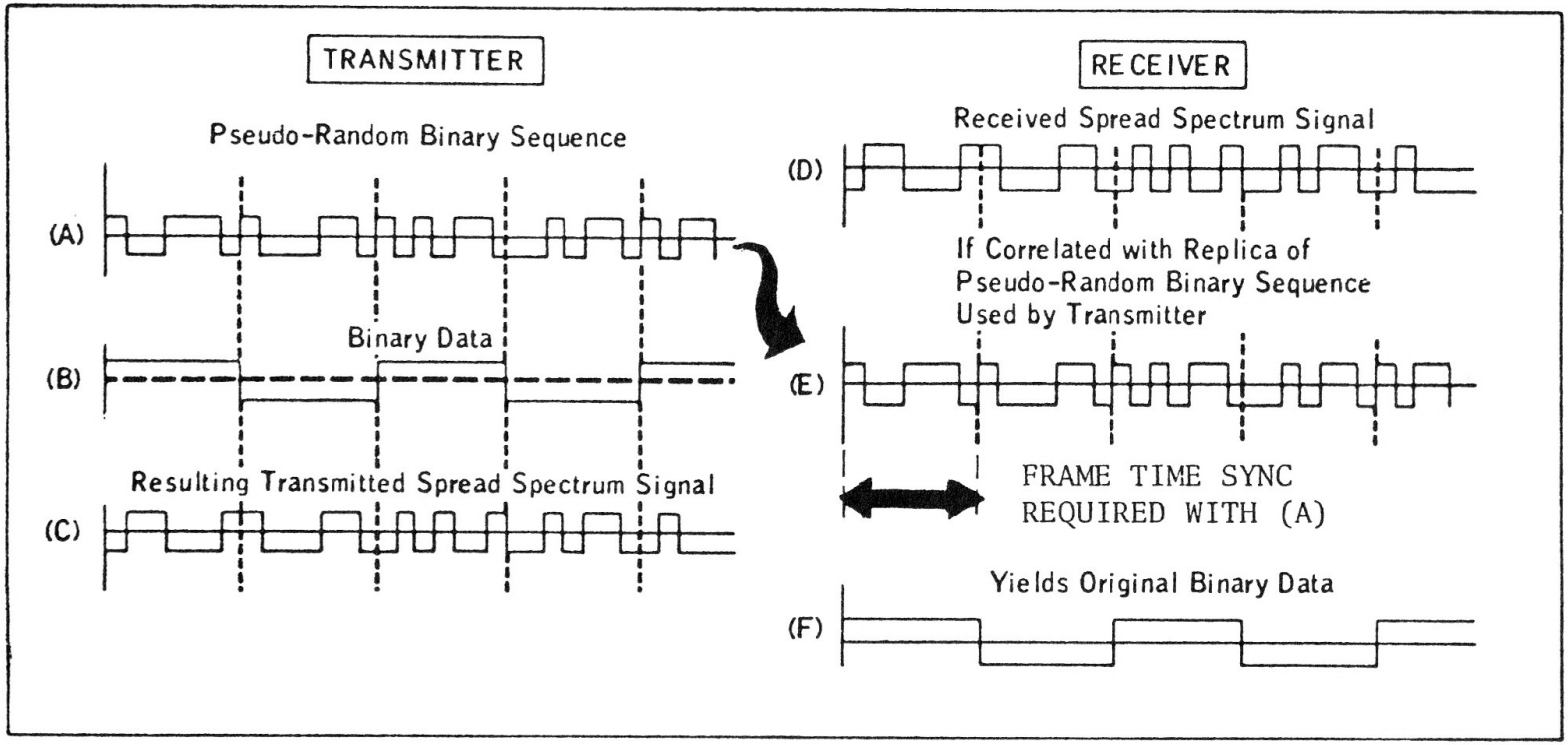
SPREAD SPECTRUM PROCESS

Ball Efratom Division



PSEUDO-NOISE (PN) DIRECT SEQUENCE SPREAD SPECTRUM

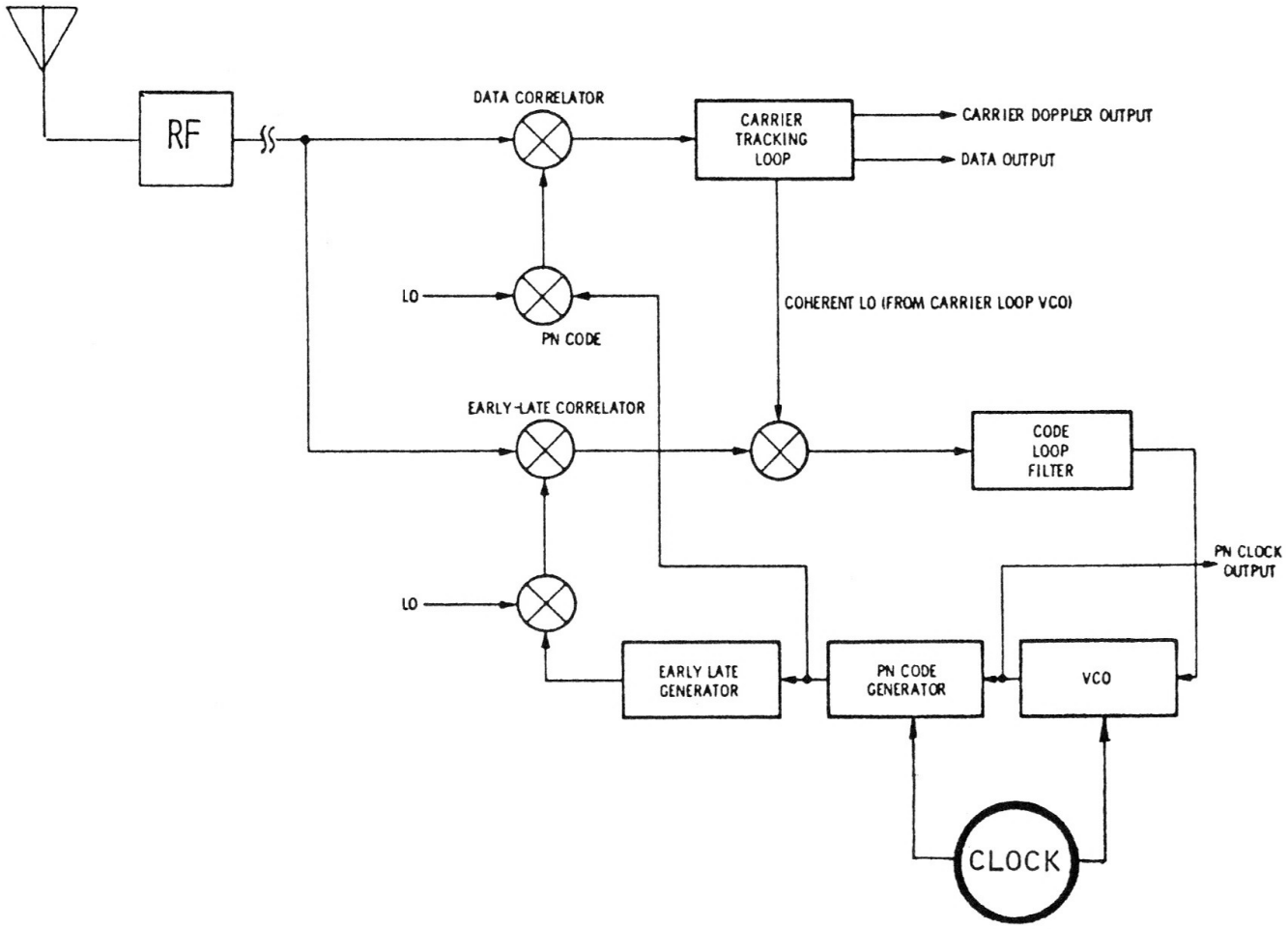
Ball Efratom Division



At the transmitter (drawing above, left), a Pseudo-Random Bit Stream (A) is generated, upon which is superimposed the Binary Data (Intelligence) that is to be communicated (B), resulting in Broadband Signal (C) that resembles noise background to a conventional radio receiver. At the receiver (drawing above, right), when an exact replica of the transmitter's Pseudo-Random Binary Sequence (E) is generated and correlated with the incoming signal (D), the Desired Binary Data (F) can be extracted.

PN-RECEIVER

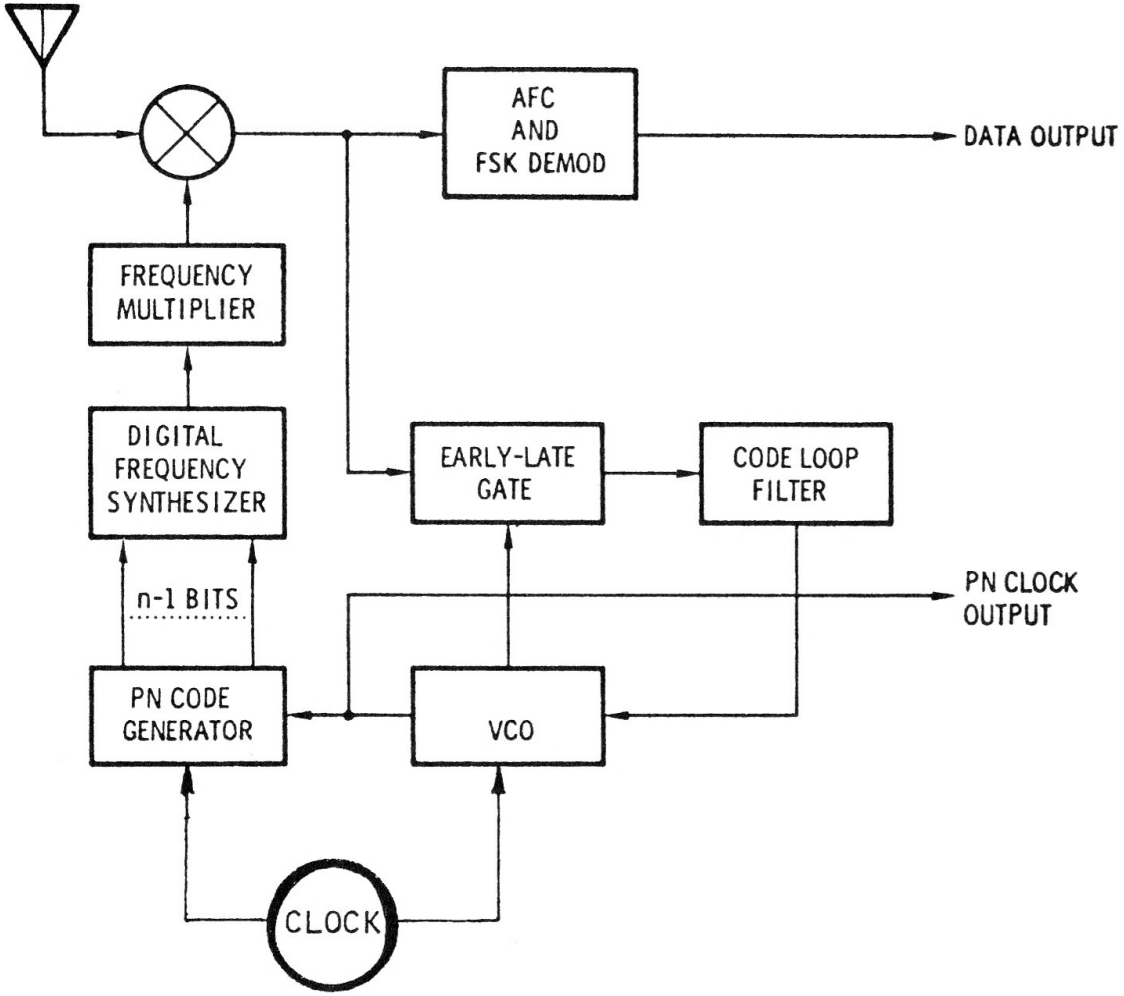
Ball Efratom Division



-MESSAGE IS IMPOSED ON WIDEBAND NOISE
-MAX. PROCESSING GAIN IN A GIVEN B.W.
-ADAPTS WELL TO BI-PHASE DATA MOD. FROM QUAD-RI PHASE PN
-CAN MEASURE TIME OF ARRIVAL OF SIGNAL FOR NAVIGATIONAL USES
-CAN DISCRIMINATE MULTIPATH
-SPECTRUM WIDTH BOUNDED BY MAXIMUM CLOCK RATE

FH-RECEIVER

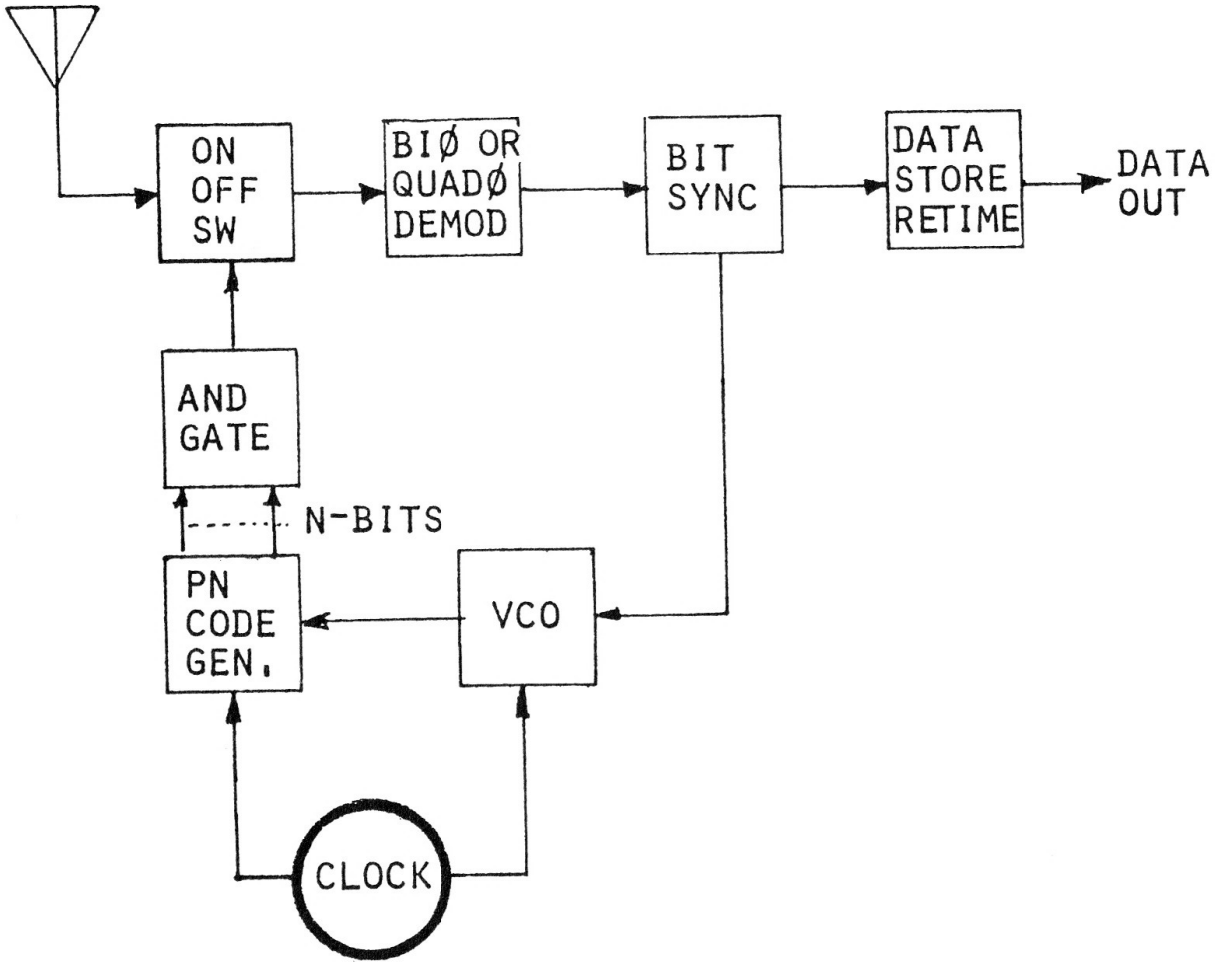
Ball Efratom Division



-CHANNELIZE AVAILABLE BANDWIDTH INTO SLOTS
-DATA PUT ON EACH PULSE, THAT OF DATA BANDWIDTH REQUIREMENT
-SINCE PULSE WIDTH IS GREATER THAN 1/TOTAL BW, FH IS NOT AS GOOD AS PN FOR TIME OF ARRIVAL
-BUT PROVIDES FASTER INITIAL SYNCHRONIZATION THAN PN
-PN CODE RATE CAN BE MUCH LESS THAN RESULTANT SPREAD BANDWIDTH, DUE TO FREQUENCY MULTIPLIER
-HAS INHERENT MULTI-ACCESS CAPABILITY
-FH WIDTH IS LIMITED BY LOGIC SPEED IN THE SYNTH

TH-RECEIVER

Ball Efratom Division



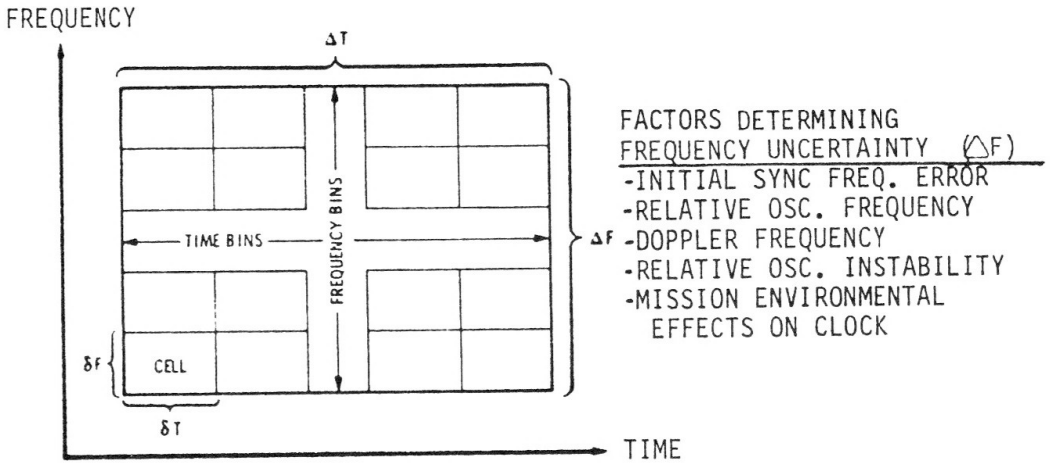
-TYPICALLY USED WITH OTHER SPREAD SPECTRUM TECHNIQUES
-CHANNELIZES VIA TIME SLOTS
-USES A BURST TRANSMISSION WITHIN THE SLOTS
-IDEAL FOR MULTIPLE ACCESS
-TYPICAL FOR TDMA & DTDMA SYSTEMS (TIME DIV. MULTI-ACC.) AND DISTRIBUTED TDMA TO ACHIEVE HIGH EFFICIENCY OF BANDWIDTH UTILIZATION
-ADAPTS WELL TO QUADRIPHASE DATA MOD.
-PULSED TRANSMITTER OPS; HI-PK PWR, LOW DUTY CYCLE

SPREAD SPECTRUM TECHNIQUES COMPARED

PN OR PRN (PSEUDO RANDOM NOISE)	FH (FREQUENCY HOPPING)	TH (TIME HOPPING)
ACCURATE TIME OF ARRIVAL MEASUREMENT (BEST FOR NAVIGATION)	WIDER SPREADING CAPABILITY BY FREQUENCY MULTIPLICATION	MULTIPLE ACCESS
HIGH MULTIPATH TOLERANCE BY DISCRIMINATION	FAST ACQUISTION OF SYNC.	HIGH BANDWIDTH EFFICIENCY
MAXIMUM PROCESSING GAIN	MULTIPLE ACCESS BY ORTHOG. FREQUENCY SLOTS	PULSED TRANSMITTER OPERATION
MORE COMPLEX AND COSTLY	MULTI-PATH TOLERANCE BY FREQUENCY DIVERSITY	
NOT BEST FOR FAST SYNC.		

ACQUISITION TIME vs. THE OSCILLATOR

FACTORS DETERMINING TIME UNCERTAINTY (ΔT)
-INITIAL SYNC TIME ERROR
-RELATIVE CLOCK TIMING (CODE EPOCH)
-PROPAGATION DELAY (POSITION UNCERTAINTY)
-RELATIVE CLOCK INSTABILITY
-MISSION ENVIRONMENTAL EFFECT ON CLOCK



δF ∝ (DETECTOR BANDWIDTH)

δT ∝ 1/(CODE RATE)

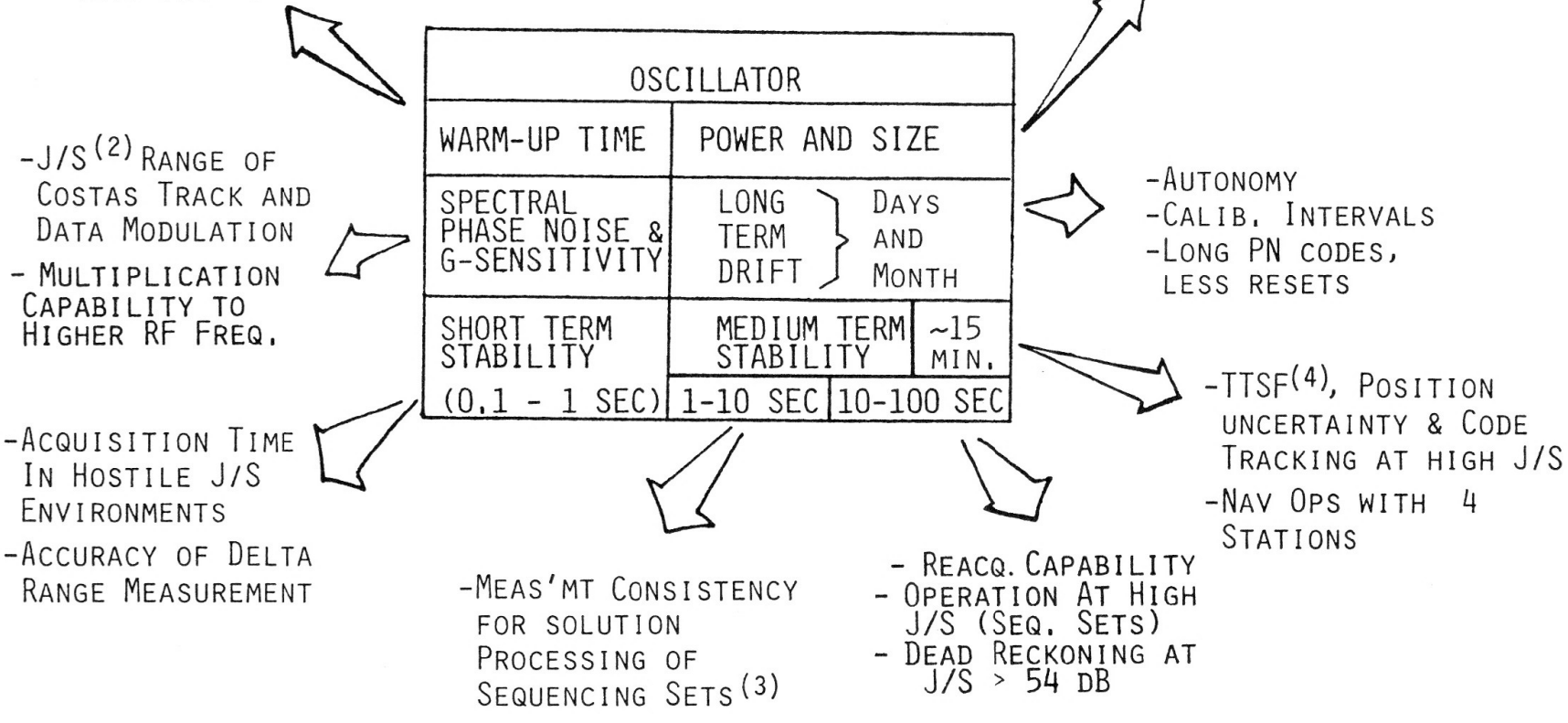
-INITIAL SYNC ERRORS IN TIME AND FREQUENCY AT BEGINNING OF MISSION
-UNCERTAINTY OF POSITION DETERMINES PROPAGATION DELAY-TIME ERROR THROUGH WHICH RCVR SEARCHES TO ACHIEVE CODE EPOCH SYNC
-RELATIVE TIME DIFFERENCE ERROR BETWEEN TRANSM. & RECEIVER
-UNCERTAINTY OF USER'S RELATIVE VELOCITY WITH RESPECT TO TRANSMITTER DETERMINES FREQUENCY ERROR DUE TO DOPPLER
-RELATIVE FREQUENCY OFFSET & DRIFT BETWEEN TRANSM. & RECEIVER
-RELATIVE CODE-EPOCH TIMING ERROR
-OSCILLATOR FREQUENCY OFFSETS FROM HOTILE ENVIRONMENTS
-OSC. SHORT TERM STABILITY AND PHASE NOISE EFFECTS ON SEARCH THROUGH FREQUENCY DOMAIN

OCILLATOR IMPACT ON NAV OR SPREAD SPECTRUM TERMINAL PERFORMANCE

Ball Efratom Division

Notes:

(1) TTFF - Time to First Fix
(2) J/S - Jamming to Signal Ratio
(3) Single channel Receivers taking one station or Sat. at a time
(4) TTSF - Time to Second Fix



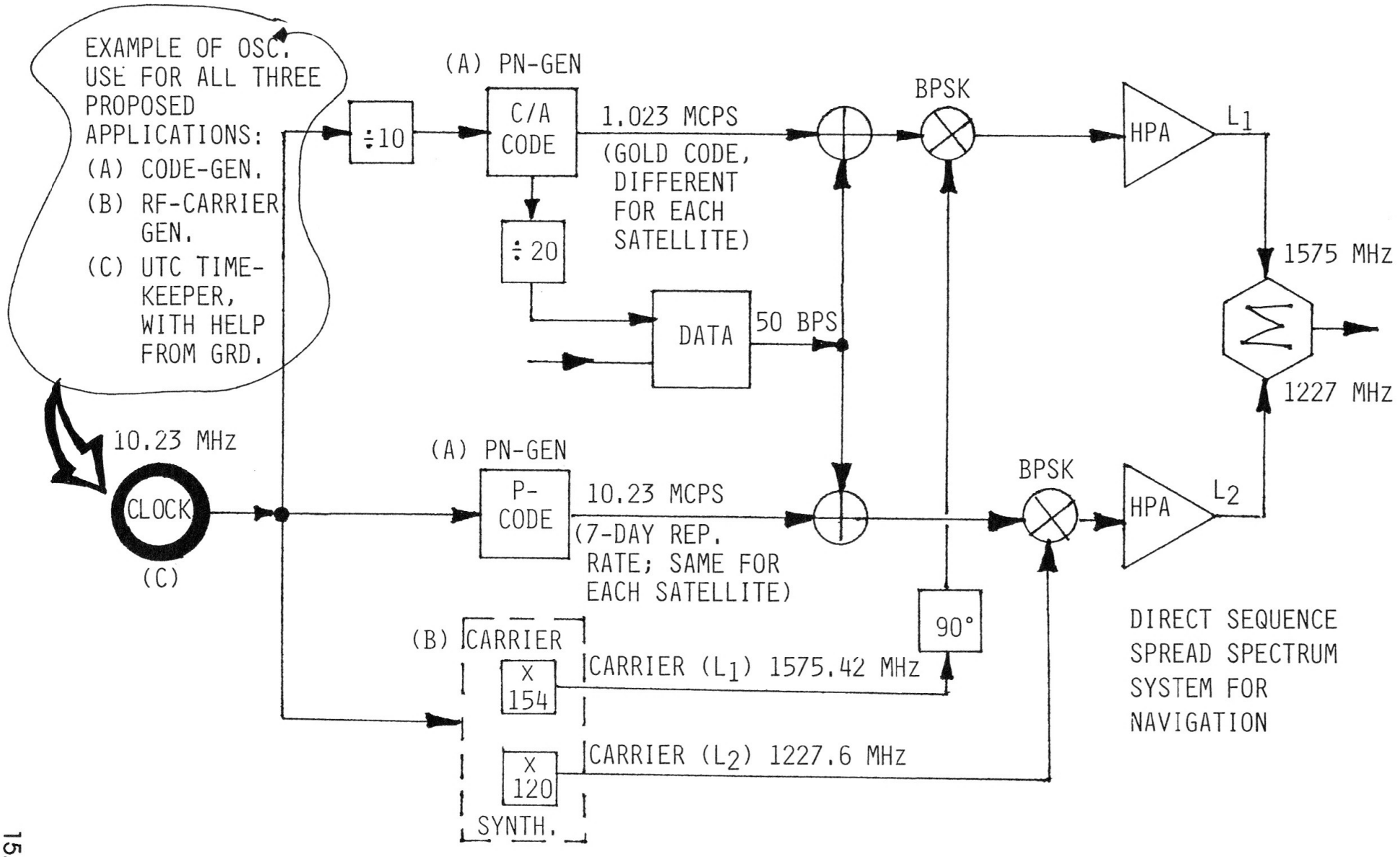
OSCILLATOR SPECS/ENVIRONMENT/SP.SP. IMPACT

Ball Efratom Division

OSCILLATOR SPECS & PERFORMANCE	ENVIRONMENTAL IMPACT ON OSC. G'S	ENVIRONMENTAL IMPACT ON OSC. ΔT	SPREAD SPECTRUM PERFORMANCE IMPACT
SHORT-TERM STAB. (O.1-1 SEC. AVE TIME) (TIME DOMAIN NOISE)	YES	NO	1. ACQUISTION TIME IN HOSTILE J/S ENVIRONMENT 2. ACCURACY OF RANGE MEASUREMENT 3. ΔRANGE MEASUREMENT CONSISTENCY OF SEQ'G SETS
MEDIUM-TERM STAB. (10-100 SEC. AVE TIME)	YES (LESS SO)	YES	1. REACQUISITION CAPABILITY OF SEQ'G SETS 2. ΔRANGE MEASUREMENT AT HOSTILE J/S 3. NAV. SOLUTION WITH 4-STATION SEQ'G SETS
PHASE NOISE (FREQ. DOMAIN NOISE)	YES	NO	1. S/N WHEN MULTIPLYING TO HI-FREQ CARRIERS 2. J /S RANGE OF COSTAS LOOP TRACKING & DATA DEMODULATION 3. BIT ERROR RATE
LONG-TERM DRIFT (FREQ. OFFSETS)	NO YES	NO YES	1. CODE REP. RATE FOR LONG MISSIONS 2. CODE CHIPPING RATE (FOR HI-RATES) 3. CALIBRATION INTERVALS & LIFE CYCLE COSTS 4. SYSTEMS/UTC TIMEKEEPING CAPABILITY

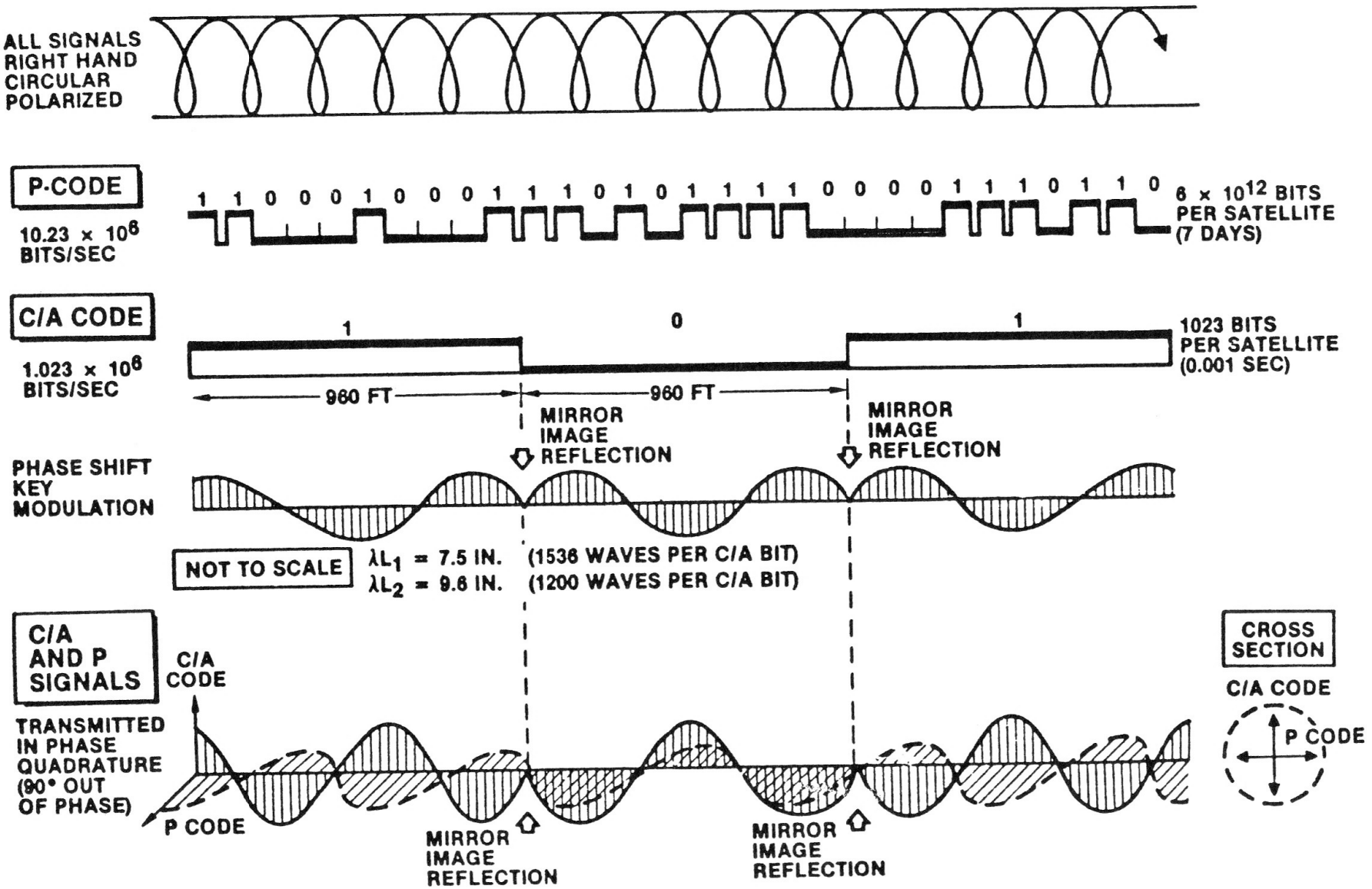
EXAMPLE SYSTEM (NAVSTAR-GPS)

Ball Efratom Division



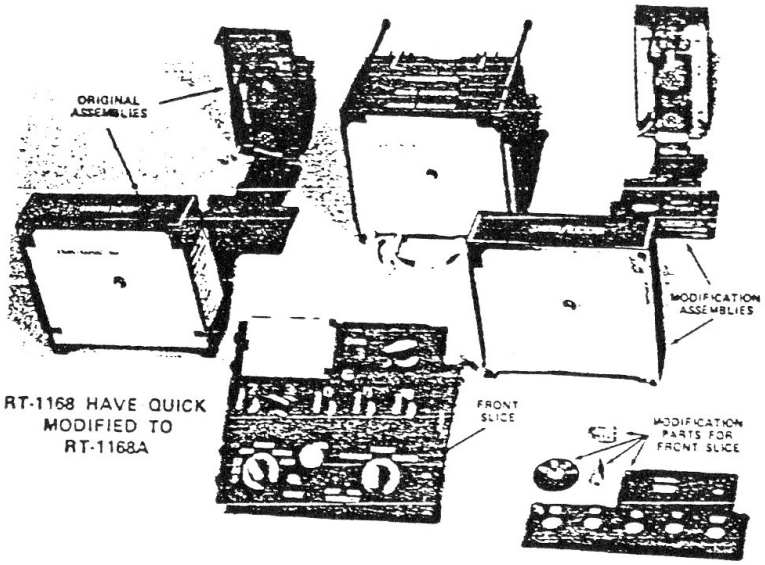
MODULATION-NAVSTAR-PRN

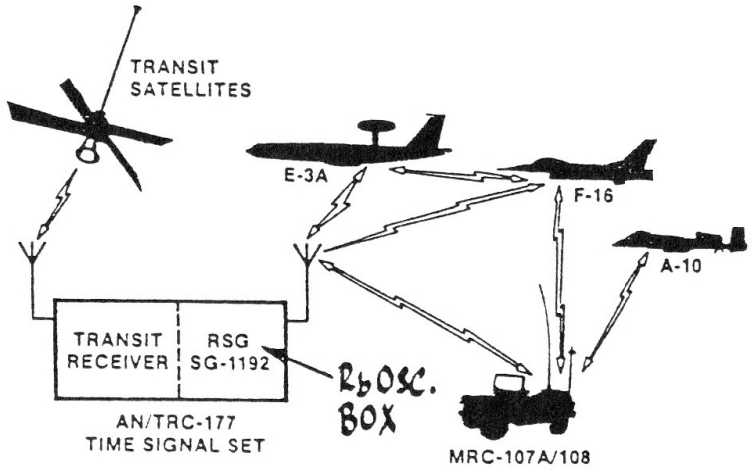
Ball Efratom Division



FH-HAVE QUICK SYSTEM EXAMPLE

Ball Efratom Division

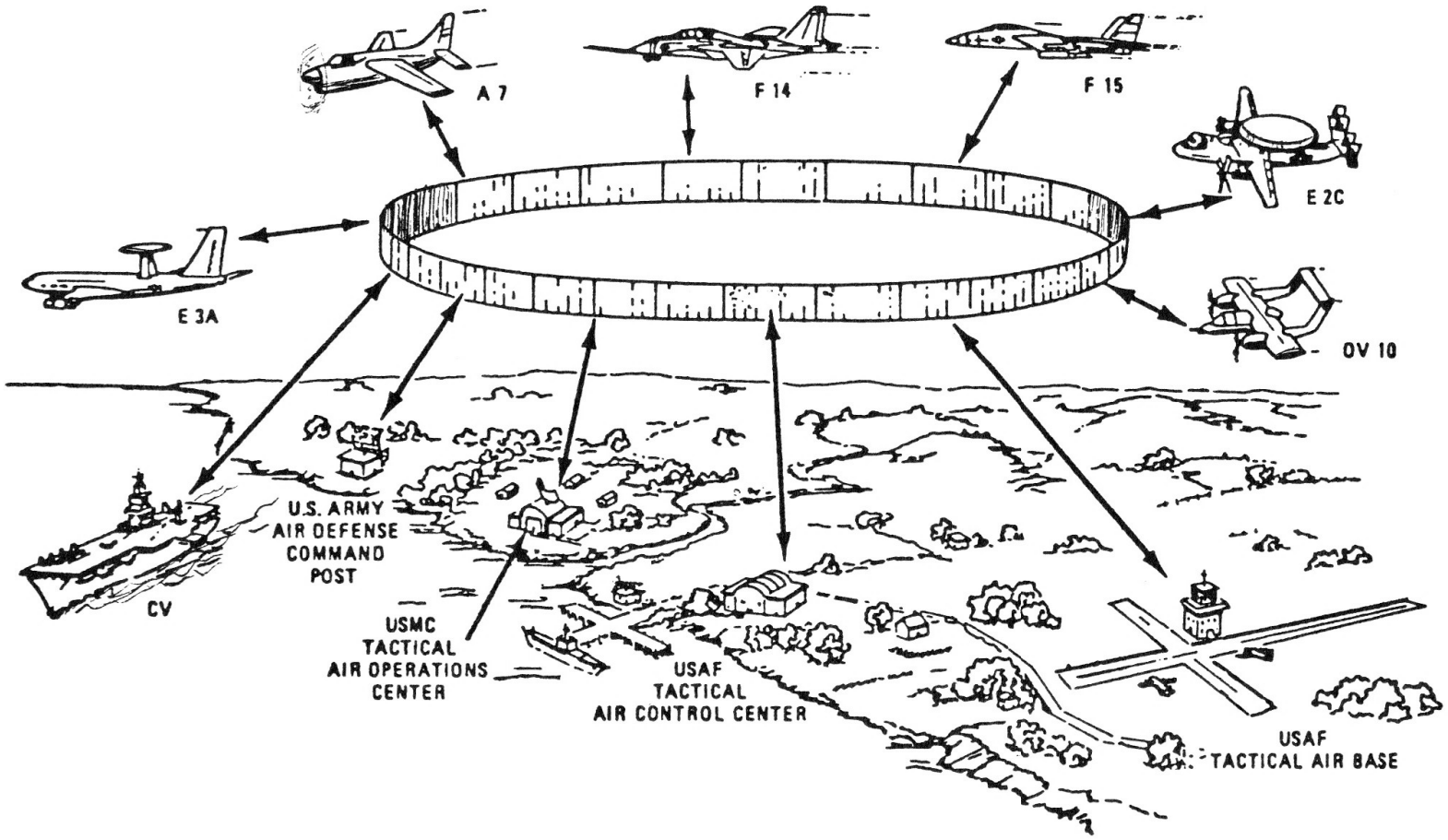




The frequency hopping scheme is implemented by storing within every HAVE QUICK radio a pattern of the frequencies to be used for a given day and utilizing this pattern according to the time of day. For every time slot in the day, there is a specific frequency which must be used for a given net, whether it is receiving or transmitting. Thus the HAVE QUICK terminals have means to store the pattern for channel use on a given day, and also an accurate clock to control the times at which the pattern is consulted.

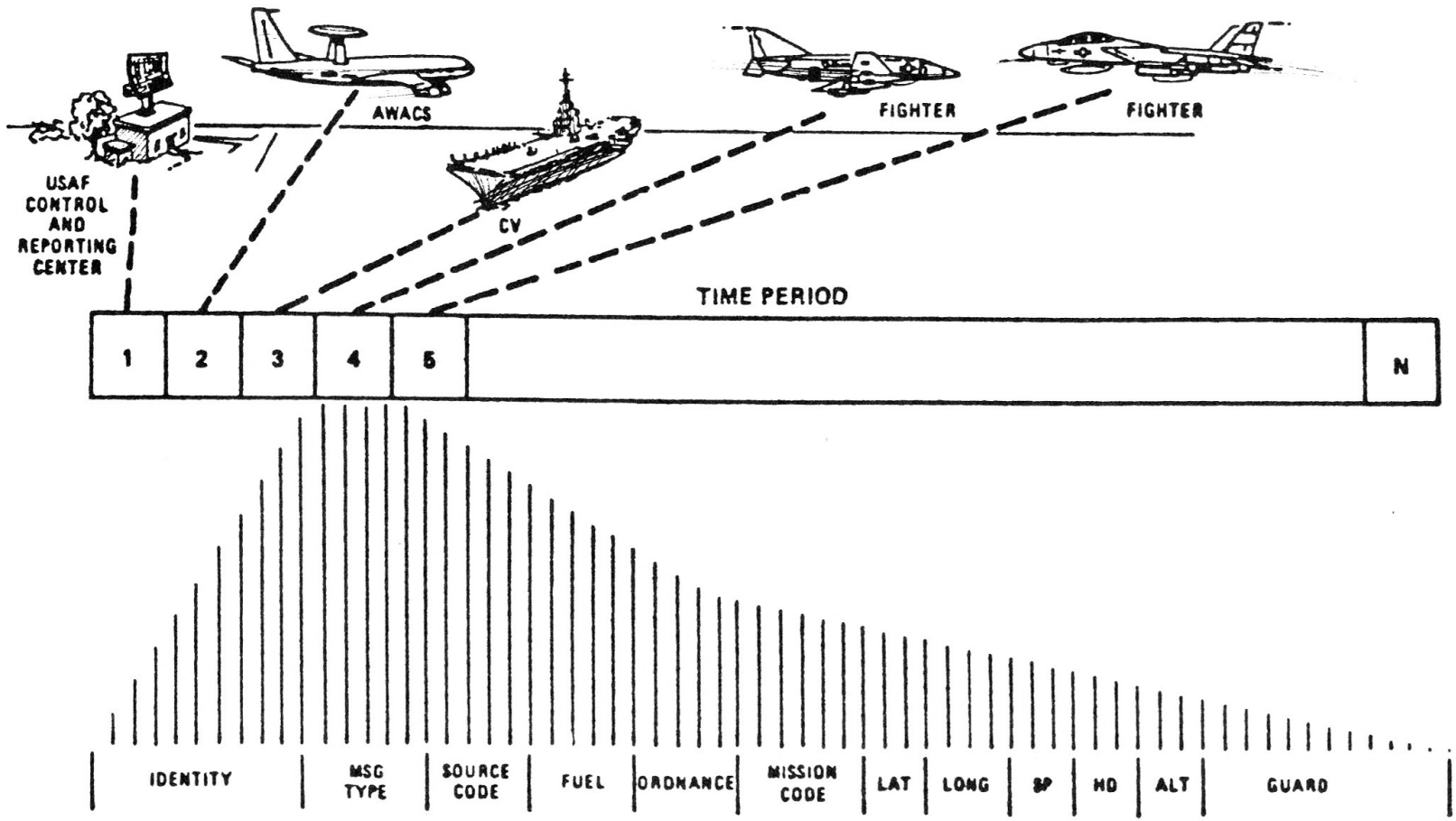
Because the frequency used at a particular instant depends on the precise time of day, both terminals of a HAVE QUICK time distribution and maintenance system accomplish this. While the HAVE QUICK system time may be set to any arbitrary standard, Coordinated Universal Time (UCT) has been adopted as a practical convenience. This permits the use of satellites as one means of obtaining time, and current plans make use of the TRANSIT satellite system. It is also possible to transfer time using portable atomic clocks, wireline communication links, or radio.

TH-JTIDS-TDMA SYSTEM



TDMA (CONTINUED)

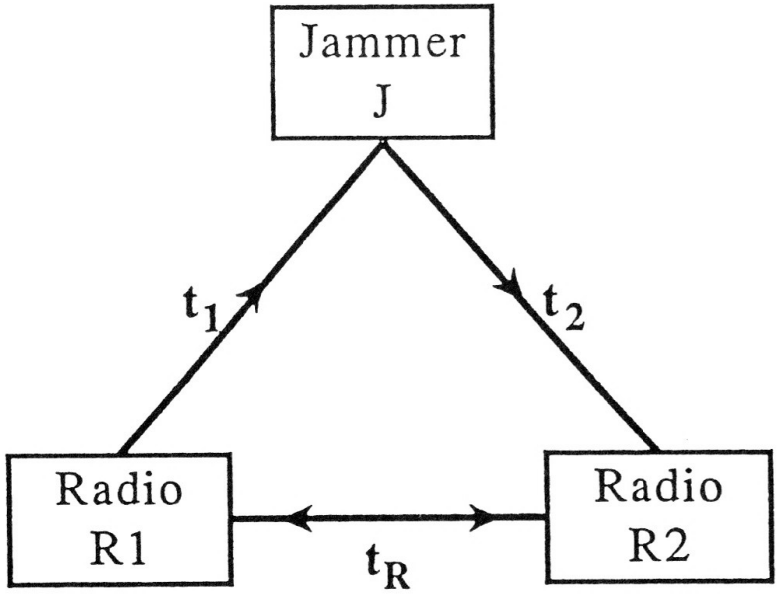
Ball Efratom Division



Typical JTIDS Position and Status Message

CLOCK FOR VERY FAST FREQUENCY HOPPING RADIO

Ball Efratom Division



To defeat a "perfect" follower jammer, need a hop rate given by:

$$t_m < (t_1 + t_2) - t_R \ ,$$

where $t_m \approx$ msg. duration/hop
$\approx$ 1/hop rate

Example

Let R1 to R2 = 1 km, R1 to J = 5 km, and J to R2 = 5 km. Then, since propagation delay = 3.3 μs/km, $t_1 = t_2 = 16.5$ μs, $t_R = 3.3$ μs, and $t_m < 30$ μs.

Allowed clock error = $0.2\ t_m$
= 6 μs.

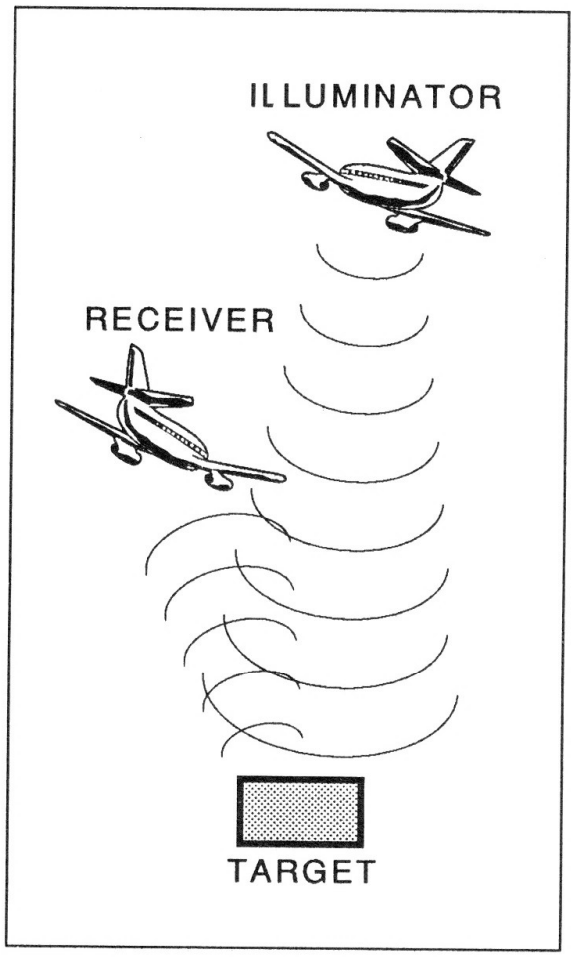
For a 4 hour resync interval, clock accuracy requirement is:

$$4 \times 10^{-10}$$

Courtesy of John Vig Army-LABCOM

BISTATIC RADAR

Conventional (i.e., "monostatic") radar, in which the illuminator and receiver are on the same platform, is vulnerable to a variety of countermeasures. Bistatic radar, in which the illuminator and receiver are widely separated, can greatly reduce the vulnerability to countermeasures such as jamming and antiradiation weapons, and can increase slow moving target detection and identification capability via "clutter tuning" (receiver maneuvers so that its motion compensates for the motion of the illuminator, creating zero Doppler shift for the area being searched). The transmitter can remain far from the battle area, in a "sanctuary". The receiver can remain "quiet".



The timing and phase coherence problems can be orders of magnitude more severe in bistatic than in monostatic radar, especially when the platforms are moving. The two reference oscillators must remain synchronized and syntonized during a mission so that the receiver knows when the transmitter emits each pulse, and so that the phase variations will be small enough to allow a satisfactory image to be formed. Low noise crystal oscillators are required for short term-stability; atomic frequency standards are often required for long-term stability.

Courtesy of John Vig, Army-LAMCOM

IDENTIFICATION-FRIEND-OR-FOE (IFF)

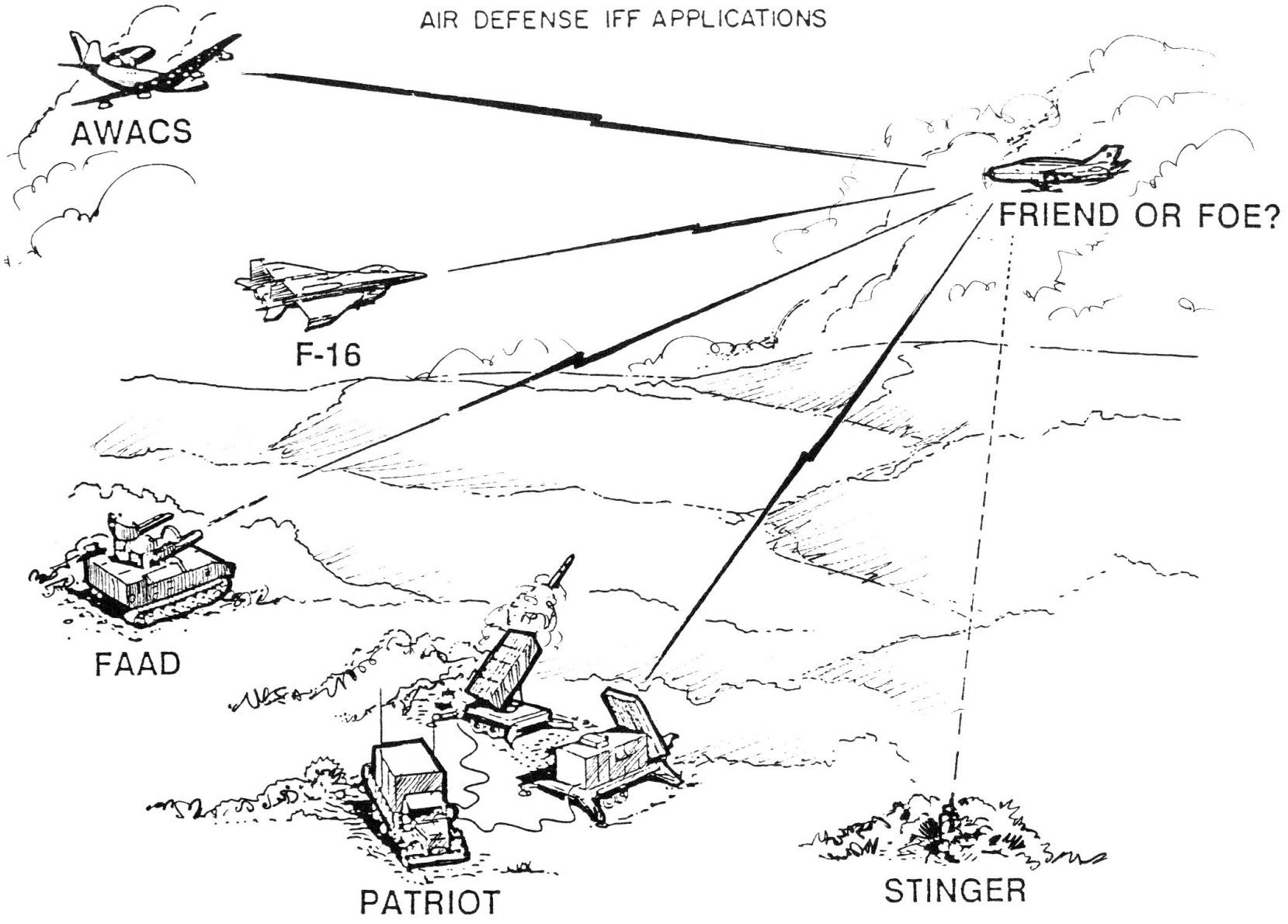
In a modern battle, when the sky is filled with friendly and enemy aircraft, and a variety of advanced weapons are ready to fire from both ground and airborne platforms, positive identification of friend and foe is critically important. For example, fratricide due to identification errors was a major problem in the 1973 Arab-Israeli war.

Current IFF systems use an interrogation/response method which employs cryptographically encoded spread spectrum signals. The interrogation signal received by a friend is supposed to result in the "correct" code being automatically sent back via a transponder on the friendly platform. The "correct" code must change frequently to prevent a foe from recording and transmitting that code ("repeat jamming"), thereby appearing as a friend. The code is changed at the end of what is called the Code Validity Interval, or CVI.

The better the clock accuracy, the shorter can be the CVI, the more resistant the system can be to repeat jamming, and the longer the autonomy period can be for users who cannot resynchronize their clocks during a mission.

Courtesy John Vig, Army-LABCOM

IDENTIFICATION-FRIEND-OR-FOE (IFF)



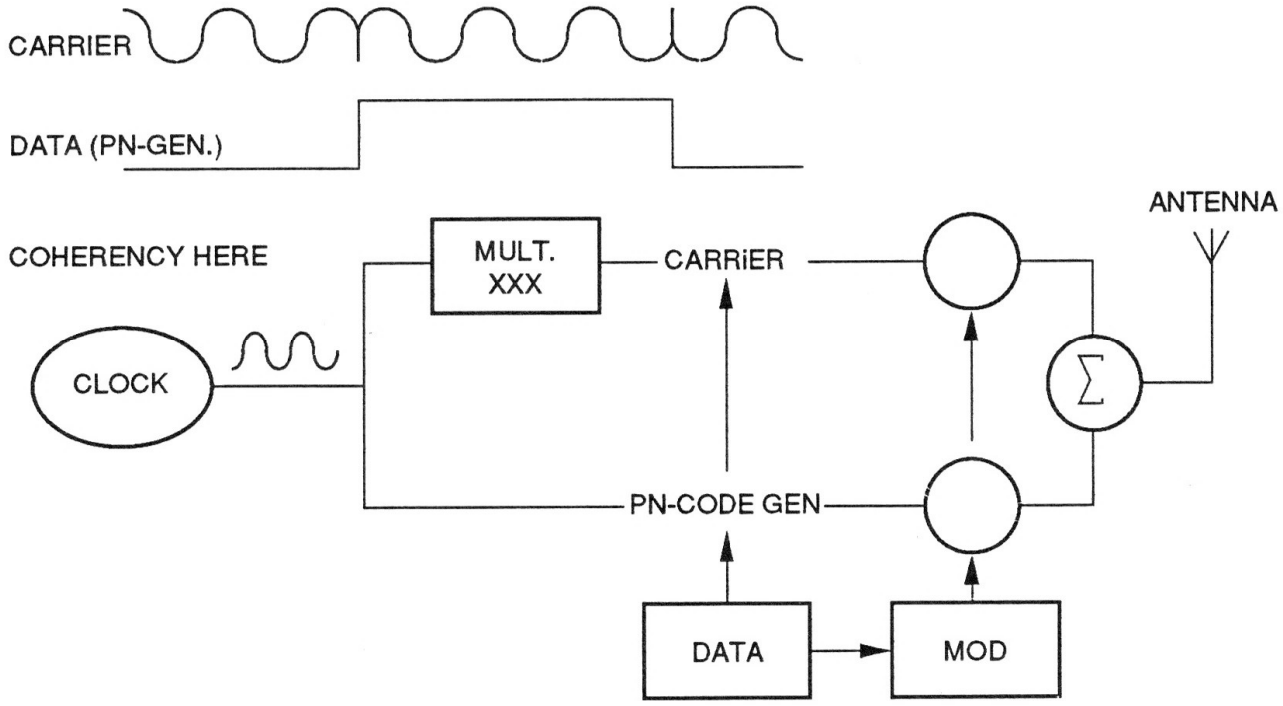
Courtesy John Vig, Army-LABCOM

WHAT IS COHERENT TRANSMISSION?

- In order to have high data rates at low bit-error rates, coherency is necessary when the spread spectrum band spread is a significant portion of the carrier frequency (i.e. 10 to 1 ratio).

- Coherent transmission means that the carrier frequency zero crossing is in-phase with the spread spectrum PN code generator zero crossing that modulates the carrier with the data.

- Using FSK or QPSK (frequency shift or phase shift keying), 1's and 0's for the digital data are created by (as one of the methods) shifting the phase.



- If carrier frequency and band spread are greatly different, for example a ratio of 100 to 1, it does not matter where the PN-code switches the carrier, relative to the zero-crossing, to create the 1 or 0. The receiver demodulator has significant noise rejection to discriminate the 1's and 0's. In the case of a low ratio, in the order of 10 to 1, switching at other than zero-crossing raises the noise floor and thus degrades the bit error rate.

WHY USE ATOMIC OSC. IN SPREAD SPECTRUM & SECURE COMM.?

TECHNICAL

-HIGHER SECURITY: NO NEED FOR RF (IN-CLEAR) TRANSFER OF TIME/CODE UPDATES

- FASTER SYNC; REDUCED SEARCH TIME IN THE TIME & FREQUENCY DOMAIN DUE TO OSC. STABILITY

- LONGER IN-SYNC MISSION

- HIGHER MULTIPATH DISCRIMINATION

- IMPROVED MULTI-ACCESS DESIGN

- POSSIBLE IMPROVEMENT IN SPREADING, DUE TO OSC. STABILITY & SPECTRAL PURITY

- MORE ACCURATE NAV SOLUTION

SYSTEMATIC

-LESS COMPLEX EQUIPMENT DESIGN; NO IN-FLT CAL CIRCUITRY & USE OF ONE OSC. FOR CODE & CARRIER

- MORE "TOLERANT" OF ENVIRONMENTAL EFFECTS ON TIME & FREQUENCY

- LESS FREQUENT CALIBRATIONS

- LOWER LIFE-CYCLE COSTS

- FOR MOST NAV & C^3 SYSTEMS, OSC. COSTS APPEAR TO FALL BETWEEN

5 TO 10% OF TERMINAL COST

IF <5%, ONE CAN ASSUME THAT THE LESS EXPENSIVE OSC. WILL BE SUPPLEMENTED WITH AN INCREASE OF COMPLEXITY OF OSC. UPDATE CIRCUITRY

IF 10% OR GREATER, IT IS MOST LIKELY AN OVERKILL, AND THE PRECISION MAY NOT BE NEEDED.

NOTES

DOMESTIC SALES, SERVICE AND SUPPORT

BASS ASSOCIATES, INC.
2901B Sandtrap Lane
Melbourne, FL 32935
(407) 259-1866
FAX: (407) 255-9777
Terr: FL

BEACON MICROWAVE
5881 Glenridge Dr./#230
Atlanta, GA 30328
(404) 256-9640
FAX: (404) 256-1398
Terr: Atlanta, GA, NC.

BEACON MICROWAVE
5950 Crooked Creek Rd./#120
Norcross, GA 30092
(404)449-8464
FAX: (813) 796-0075
Terr: E. TN, GA, SC.

BEACON MICROWAVE
7501 S. Memorial Pkwy/#105
Huntsville, AL 35802
(205) 880-2381
FAX: (205) 883-9516
Terr: AL, MS, W. TN

BEACON MICROWAVE
208 Marginal St.
Sylvester, GA 31791
(912) 776-4100
FAX: (912) 776-0831
Terr: Mid/So. GA

BEACON MICROWAVE
1221 W. Campbell Rd./#161
Richardson, TX 75080
(214) 437-1505
FAX: (214) 437-5874
Terr: Top half TX, Top half LA, AR, OK

BEACON MICROWAVE
1315 Sam Bass Circle/#B-4
Round Rock, TX 78681
(512) 244-6675
FAX: (512) 244-1883
Terr: Lower half TX, Lower half LA

CDB ENTERPRISES
675 W. Jericho Turnpike
Huntington, NY 11743
(516) 692-5200
FAX: (516) 351-1058
Terr: CT, NY, NJ

HOWARD ASSOCIATES
P.O. Box 408
Parker, CO 80134
(303) 841-5755
FAX: (303) 841-9272
Terr: CO, UT

KOLM MARKETING
75 Dior Terrace
Los Altos, CA 94022
(415) 948-2635
FAX: (415) 948-6284
Terr: N. CA

MAYCO, INC
11910 Central S.E.
Albuquerque, NM 87123
(505) 299-4002
FAX: (505) 299-0153
Terr: NM, El Paso County, TX, AZ

SCIENTIFIC DEVICES - WEST
16882 Bolsa Chica St.
Huntington Beach, CA 92649
(714) 840-3501
FAX: (714) 840-3500
Terr: So. CA, Clark Co., NV

SELTECH
13228 S.E. 30th St./#C-1
Bellevue, WA 98005
(206) 746-7970
FAX: (206) 644-8422
Terr: WA, OR

STEMLER ASSC., INC.
6707 Whitestone Rd.
Baltimore, MD 21207
(410) 944-8262
FAX: (410) 944-4840
Terr: Wash. D.C., VA, MD, E. PA

TX SALES, INC
P.O. Box 5298
Fort Wayne, IN 46895
(219) 489-4447
FAX: (219) 489-6934
Terr: IN, OH, IA, MI, IL, KY

WAYLAND ENG. SALES
2 Evergreen Rd
Natick, MA 01760
(508) 655-6080
FAX: (508) 653-1573
Terr: MA, CT, NH, MN, RI, VT

INTERNATIONAL*

*SEE BACK COVER FOR INTERNATIONAL LOCATIONS

EFRATOM FACILITIES

Efratom Division
3 Parker
Irvine, CA 92718-1605
(714) 770-5000
FAX: (714) 770-2463

Efratom Elektronik-GmbH
Fichtenstrasse 25,
8011 Hofolding
(Munich) Germany
49-08104-9040
FAX: 49-08104-9918

Efratom Division
Edward Yrisarri, Jr.
1445 Melody Lane
Roanoke, TX 76262
(817) 379-6070
FAX: (817) 431-0153

Efratom Division
Richard T. Boswell
P.O. Box 884
Lynchburg, VA 24505
(804) 846-1400
FAX: (804) 846-3299

INTERNATIONAL SALES, SERVICE AND SUPPORT

THE DINDIMA GROUP PTY., LTD.
P.O. Box 106
Vermont, Victoria 3133
AUSTRALIA
61-3-873-4455, FAX: 61-3-873-4749

SAIT-ELECTRONICS
Chaussee de Ruisbroek 66
B-1190 Bruxelles
BELGIUM
32-2-370-5311, FAX: 32-2-378-2539

TELE-RADIO SYSTEMS, LTD.
620 Alden Road, #102
Markham, Ontario
L3R 9R7
CANADA
(416) 946-1705
FAX: (416) 946-1709

TELE-RADIO SYSTEMS, LTD.
10651 Shellbridge Way, #107
Richmond, B.C. V6X 2WB
CANADA
(604) 273-4300
FAX: (604) 273-3414

ERLING B. IBSEN
Metalbuen 28
DK-2750 Ballerup,
DENMARK
45-42978111, FAX: 45-44680626

EUROTRONICS (UK) LTD.
Lattice House, Baughurst Road
Baughurst, Basingstoke
Hampshire RG26 5LL
ENGLAND
44-(0)734-819970
FAX: 44-(0)734-819786

JUTEL OY
Teknologiante 11
SF-90570 Oulu
FINLAND
358-81-551-4801,
FAX: 358-81-551-4810

RACAL SYSTEMS ELECT, s.a.
18, avenue Dutartre
F-78150 Le Chesnay
FRANCE
33-1-39-558-888
FAX: 33-1-39-556-735

UNVERDROSS TECHNIK (UTG)
Tutzinger Hof Platz 6
Postfach 17 49
D-8130 Starnberg
GERMANY
49-81-51-21198
FAX: 49-81-51-21190

DYNAMAC (INDIA) PVT, LTD.
E-40/7 Okhla Ind. Area Phase II
New Delhi - 110 - 020
INDIA
91-11-683-1174
FAX: 91-11-683-1553

RANGECOM ELECTRONICS, LTD.
1 Habossem Street
Ramat - Hasharon 47226
ISRAEL
972-3-5406697
FAX: 972-3-5402733

RACAL SYSTEMS ELETT., s.r.l.
Via Roma, 108 / Pal.E1
20060 Cassina de'Pecchi,
Milano
ITALY
39-2-951-4717, FAX: 39-2-951-4522

RACAL SYSTEMS ELETT., s.r.l.
Via Vito Giuseppe Galati, 100/C
00155 Roma
ITALY
39-6-406-3050, FAX: 39-6-407-8341

JAPAN
(Please contact Ball Efratom factory)

SAMA ELECTRONICS CORP
4th Fl. Dae Pyung Bldg.
19-11. Pil-Dong 2GA, Joong-Ku
Seoul
KOREA
82-2-271-2761, FAX: 82-2-271-2764

MARINE-AIR SYSTEMS, LTD.
P.O. Box 30-248, Lower Hutt
Wellington
NEW ZEALAND
64-4-569-2170, FAX: 64-4-566-1247

NORTRONICOM A/S
P.O. Box 33 Manglerud
N0612 Oslo 6
NORWAY
47-2-680910, FAX: 472-68-1887

OCEANAV PTE, LTD.
Block 2001, Unit 02-28
Butik Batok Industrial Park "A"
SINGAPORE
65-562-3005, FAX: 65-560-5563

BENAVIA AB
P.O. Box 1122
S-171 22 Solna
SWEDEN
46-8-735-0450, FAX: 46-8-734-0303

LUMAX INTL. CORP., LTD.
7th FL., No. 52, Sec 3, Nankong Rd
Taipei, R.O.C.
TAIWAN
886-2-788 3656
FAX: 886-2-782-7369

INTER MUHENDISLIK & DANISMANLIK
T & M Division, Bagdat Cad NR 301
81060 Istanbul
TURKEY
90-1-385-75-33
FAX: 90-1-350-32-43

EFRATOM FACILITIES

Efratom Division
3 Parker
Irvine, CA 92718-1605
(714) 770-5000
FAX: (714) 770-2463

Efratom Elektronik-GmbH
Fichtenstrasse 25,
8011 Hofolding
(Munich) Germany
49-08104-9040
FAX: 49-08104-9918

Efratom Division
Edward Yrisarri, Jr.
1445 Melody Lane
Roanoke, TX 76262
(817) 379-6070
FAX: (817) 431-0153

Efratom Division
Richard T. Boswell
P.O. Box 884
Lynchburg, VA 24505
(804) 846-1400
FAX: (804) 846-3299